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PREDICTED OIL RECOVERY BY WATERFLOOD
AND GAS DRIVE, BRADFORD THIRD AND SARTWELL
SANDS, SARTWELL OILFIELD, McKEAN COUNTY, PA.

By John R. Duda, William K. Overbey, Jr.,
and Harry R. Johnson



UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

April 1967

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Walter R Howard
Director

PREDICTED OIL RECOVERY BY WATERFLOOD
AND GAS DRIVE, BRADFORD THIRD AND SARTWELL
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* * * * * report of investigations 6943



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PREDICTED OIL RECOVERY BY WATERFLOOD AND GAS DRIVE,
BRADFORD THIRD AND SARTWELL SANDS,
SARTWELL OILFIELD, McKEAN COUNTY, PA.

by

John R. Duda,¹ William K. Overbey, Jr.,² and Harry R. Johnson³

ABSTRACT

The Bureau of Mines Morgantown Petroleum Research Laboratory, with the cooperation of the Penn York Oil Company, cored the Dewdrop, Bradford Third, Lewis Run, and Sartwell sands in the Sartwell oilfield, McKean County, Pa. This report contains a review of the geology and depositional history of the field and an evaluation of the feasibility of secondary recovery of oil from the Bradford Third and Sartwell sands by waterflood or gas drive.

Core analysis, geologic data, and electrical and radioactivity logs were used to evaluate the reservoir characteristics. Reservoir geometry, rock properties, fluid characteristics and saturations, and relative permeability-saturation relationships were used to assess the floodability of these two sands. The results of this study indicate that between 53,000 and 61,000 barrels of oil can be recovered by water or gas injection. The success of a waterflood or gas drive will depend on the field injection rates of the reservoirs comprising this oilfield. Following an economic evaluation, additional field work is recommended to further test the floodability of the reservoir.

INTRODUCTION

The most common primary-drive mechanism in Appalachian area reservoirs is solution gas. This is the least efficient of the major natural drives and

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recoveries only 5 to 25 percent of the oil initially in place (6).⁴ The Bureau of Mines is investigating the susceptibility of selected Appalachian region oil reservoirs to secondary recovery by waterflood or gas drive. The objective of these studies is to increase ultimate recovery from pressure-depleted reservoirs.

The selection of a reservoir for study is made by the Bureau of Mines with the advice of a technical advisory committee composed of representatives from industry, universities, and a state geological survey within the Appalachian area. After a reservoir has been selected, the Bureau gathers all pertinent information on the history of the area. A well is then cored and logged, and reservoir fluid samples are obtained. Routine core analysis and other special tests, such as relative permeability, are then conducted. These data are assembled into a comprehensive report (5, 21) analyzing the susceptibility of the reservoir to proven methods of stimulation such as waterflood or gas drive.

The Sartwell oilfield was selected for study because oil production from this field by primary means is approaching the economic limit.

ACKNOWLEDGEMENTS

The cooperation of Mr. Azel Ford and the Penn York Oil Company in providing data for this report is gratefully acknowledged. Also recognized is the assistance provided by the Industry Technical Advisory Committee under the sponsorship of the Pennsylvania Grade Crude Oil Association.

GENERAL GEOLOGY

Location and Topography

The Sartwell oilfield, located on the northern flank of the Smethport anticline in north central McKean County, Pa., occupies portions of Annin, Eldred, and Keating Townships (fig. 1). The center of the Sartwell oilfield is about 6 miles northeast of the town of Smethport.

McKean County lies within the Allegheny Mountain section of the Appalachian Plateaus Physiographic Province. The somewhat rugged topography is typical of a plateau that has been dissected to maturity by erosion. The area is dendritically drained by many small streams which empty into the Allegheny River. The meandering Allegheny River has built a flood plain that varies from 1 to 1½ miles wide and provides a break from the undulating hill terrain. Maximum relief of the area is approximately 850 feet.

Areal Extent and Development

The Sartwell oilfield has an area of almost 2,660 acres (1, 12). The field was discovered in 1898 and produces from the Sartwell sand at

⁴Underlined numbers in parentheses refer to items in the list of references at the end of this report.

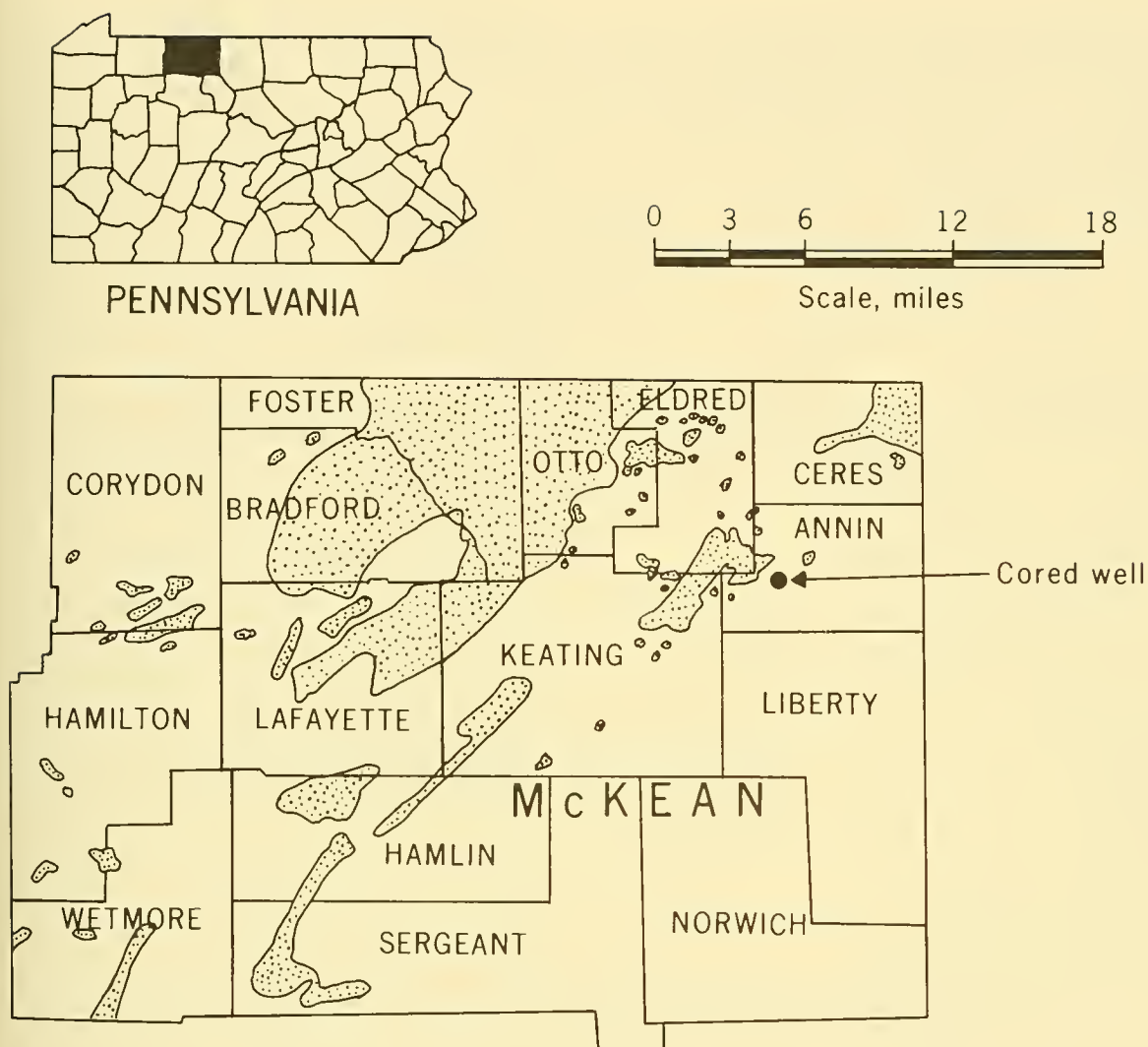


FIGURE 1. - Oil-Productive Areas in McKean County, Pa.

approximately 1,600 feet, and in portions of the field from the Bradford Third sand at 1,200 feet, both of Upper Devonian age. During early development, initial production ranged from 3 to 100 barrels of oil per day (12). About 350 wells were drilled in the field with an average well spacing of 500 feet. An estimated 40 to 50 wells are still producing.

The Bradford Third, Lewis Run, and Sartwell sands are gas productive updip from the Sartwell oilfield (fig. 2) (16).

Surface Stratigraphy

Rocks of Mississippian and Devonian age are exposed in the vicinity of the Sartwell oilfield. The Olean Conglomerate, or Olean Sandstone, belonging to the Pottsville Group of earliest Pennsylvanian age (fig. 3) is found on the hilltops near Smethport. The Pocono Group of Mississippian age, consisting of

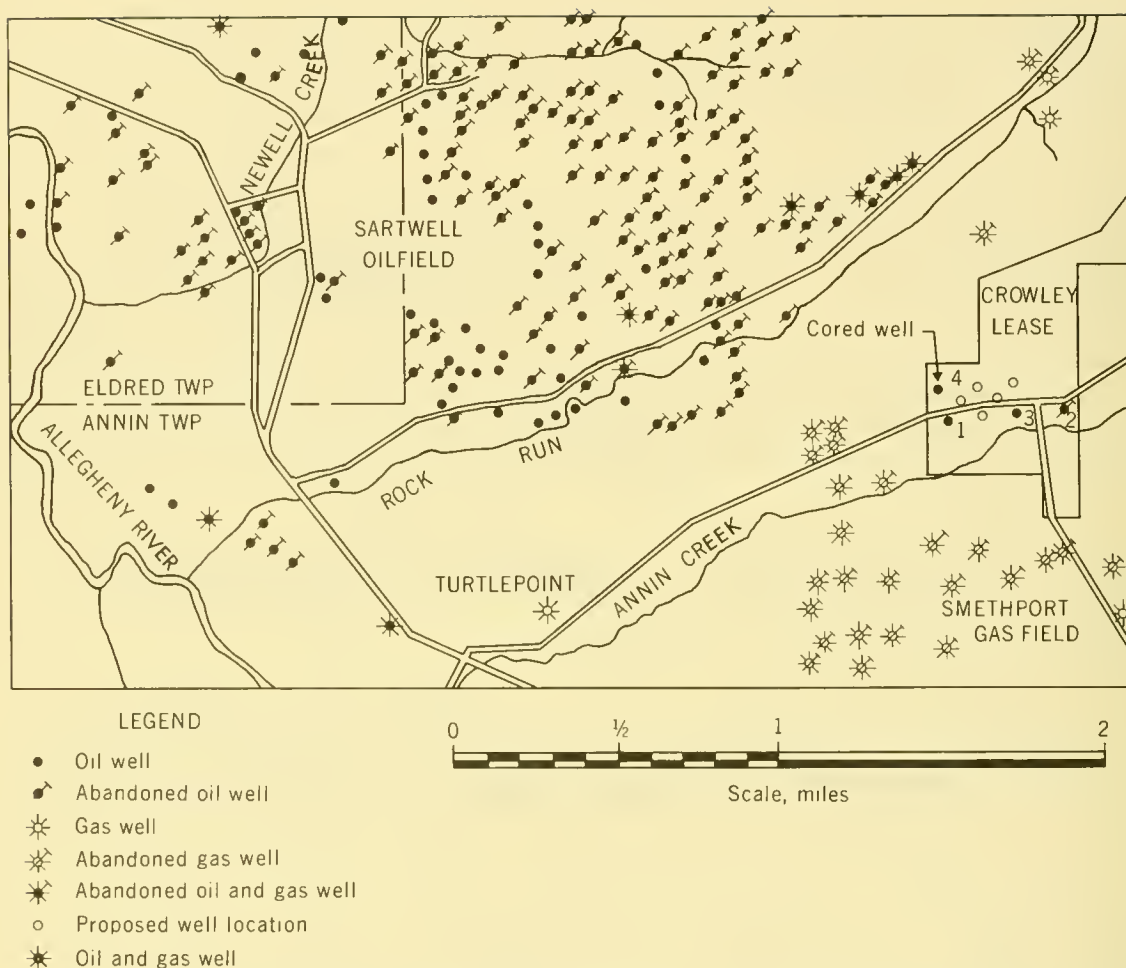


FIGURE 2. - Map of Study Area comprising Portions of Sortwell Oilfield and Smethport Gasfield, McKean County, Pa.

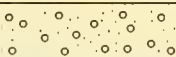
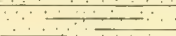
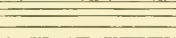
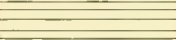
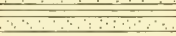
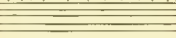
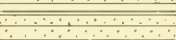
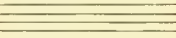
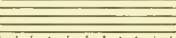
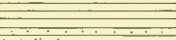
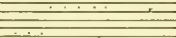
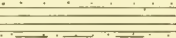
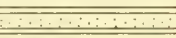
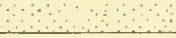
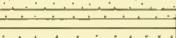
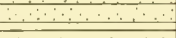
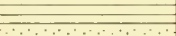
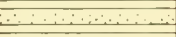
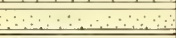
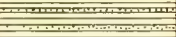
conglomerates and sandstones of the Knapp Formation, is found on the hilltops in the immediate vicinity of the field. Gray and brown shales and sandstones belonging to the Conewango and Conneaut Groups of Upper Devonian age are exposed on the hillsides and valley floor.

Surface Structure

Surface rocks in the area of the Sartwell oilfield dip approximately 45 feet per mile to the southwest paralleling the axis of the Smethport anticline (1). The northeast-southwest trending anticline lies to the southeast of the oilfield. The Smethport gasfield straddles the axis of the anticline.

Subsurface Stratigraphy

The upper boundary of the Conneaut Group, which crops out on the hillsides of the study area, is the base of the Tanners Hill Red Beds. The lower boundary (in the subsurface) designated as the base of the Bradford First sand

NORTHWESTERN PENNSYLVANIA*			GENERALIZED GEOLOGIC COLUMN		ALLEGANY COUNTY, NEW YORK**							
SYSTEM	GROUP	FORMATION	ROCK COLUMN	DRILLERS' TERMS	FORMATION	GROUP	SYSTEM					
PENNSYLVANIAN	POTTSVILLE	OLEAN CGL.		Olean Conglomerate	OLEAN CGL.	POTTSVILLE	PENNSYLVANIAN					
MISSISSIPPIAN	POCONO	KNAPP		Knapp	KNAPP	POCONO	MISSISSIPPIAN					
UPPER DEVONIAN	CONEWANGO	OSWAYO		Riceville Shale	OSWAYO	CONEWANGO	UPPER DEVONIAN					
		VENANGO		Cattaragus	CATTARAGUS							
												
												
	CONNEAUT	CHADAKOIN		Tanners Hill Red Zone	WOLF CREEK CGL.	CONNEAUT						
				Pink Rock	CHADAKOIN							
		GIRARD		Warren First	HINSDALE SS.							
				Warren Second	WELLSVILLE							
		CUBA SS.		Bradford First (Glade)	CUBA							
	CANADAWAY	NORTH-EAST SH		Watsonville Clarendon (Dewdrop) Chipmunk (Cherry Grove Tiona)	MACHIAS			CANADAWAY				
		SHUMLA SS.		Bradford Second	RUSHFORD LAKE							
		WEST-FIELD SH		Harrisburg Run	PERRYSBURG							
		LAONA SS.		Upper Richburg Stray						RUSHFORD SS.		
		GOW-ANDA SH		Richburg Stray						CANEADEA SH		
				Bradford Third								
				Lewis Run								
		DUNKIRK SH		Upper Kane						CANASERAGA SS.		
				Lower Kane								
				Sartwell				HUME SH.				
				Haskill	DUNKIRK SH.							

*After Willard, 1939

LEGEND

**After Manspeizer, 1963

	SANDSTONE		SHALE
	SHALY SANDSTONE		BLACK SHALE
	CONGLOMERATE		UNCONFORMITY

FIGURE 3. - Generalized Geologic Column and Stratigraphic Correlation of Subsurface Rocks in the Sartwell Oilfield With Those of Northwestern Pennsylvania and Allegany County, N.Y.

is reported by Fettke (9) as the stratigraphic equivalent of the Cuba Sandstone (outcrop) of Allegany County, N. Y., and the Queen or Glade Sand of Warren County, Pa.

The Canadaway Group, consisting mostly of marine shales and sandstones found between the base of the Bradford First sand and the base of the black Dunkirk Shale, is about 1,300 feet thick (from well records) in the study area. Included in this group are 13 different discontinuous sandstone lenses that are oil or gas productive in various parts of McKean and nearby counties. Figure 3 shows the relative stratigraphic position of these sands in the Sartwell oilfield area.

Beneath the Canadaway Group lie the "Chemung" and "Portage" Groups of Upper Devonian age consisting mostly of shales and interbedded sandstone of marine origin (22). The recently published (1960) geologic map of Pennsylvania merged the "Chemung" and "Portage" Groups with the Canadaway Group and redesignated them as the Canadaway Formation (14).

Older formations found below the Upper Devonian are not completely evaluated as to their oil and gas potential and will not be discussed.

Subsurface Structure

The productive sands in the study area dip gently, approximately 50 to 100 feet per mile, to the northwest as shown in cross section A-A' of figure 4 and the structure map in figure 5 (16). Structure maps of the study area contoured on top of the Bradford Third and the bottom of the Sartwell sands, based on drillers' logs, are shown in figures 6 and 7, respectively.

Depositional Environment

Fettke (9) has noted that the Upper Devonian Bradford Third sands were deposited under marine conditions, as evidenced by the presence of marine fossils in the main sand body and a very fossiliferous cap rock at the top of the sand body. He further described the conditions of deposition as follows:

When the sand was laid down a shallow Upper Devonian sea covered the area. The shore line of this ancient sea probably was no very great distance to the east and southeast of the district. Streams, rendered sluggish by having to flow across a broad low-lying coastal plain that bordered this sea on the east, washed relatively fine sediments, including fine sand, silt, and clay into it. The sand accumulated in greatest volume opposite the mouths of the larger streams, and the finer material was washed farther out into the sea. Waves and shore currents, however, also played an important role in further sorting the sand from the silt and clay and distributing it more widely over the shallow sea floor near the shore. The positions of the mouths of the streams that brought in the sediments, the configuration of the sea floor, tidal currents, and the direction and strength of the littoral currents were all factors in determining the distribution, size, thickness, and trends of the sand bodies as they occur today.

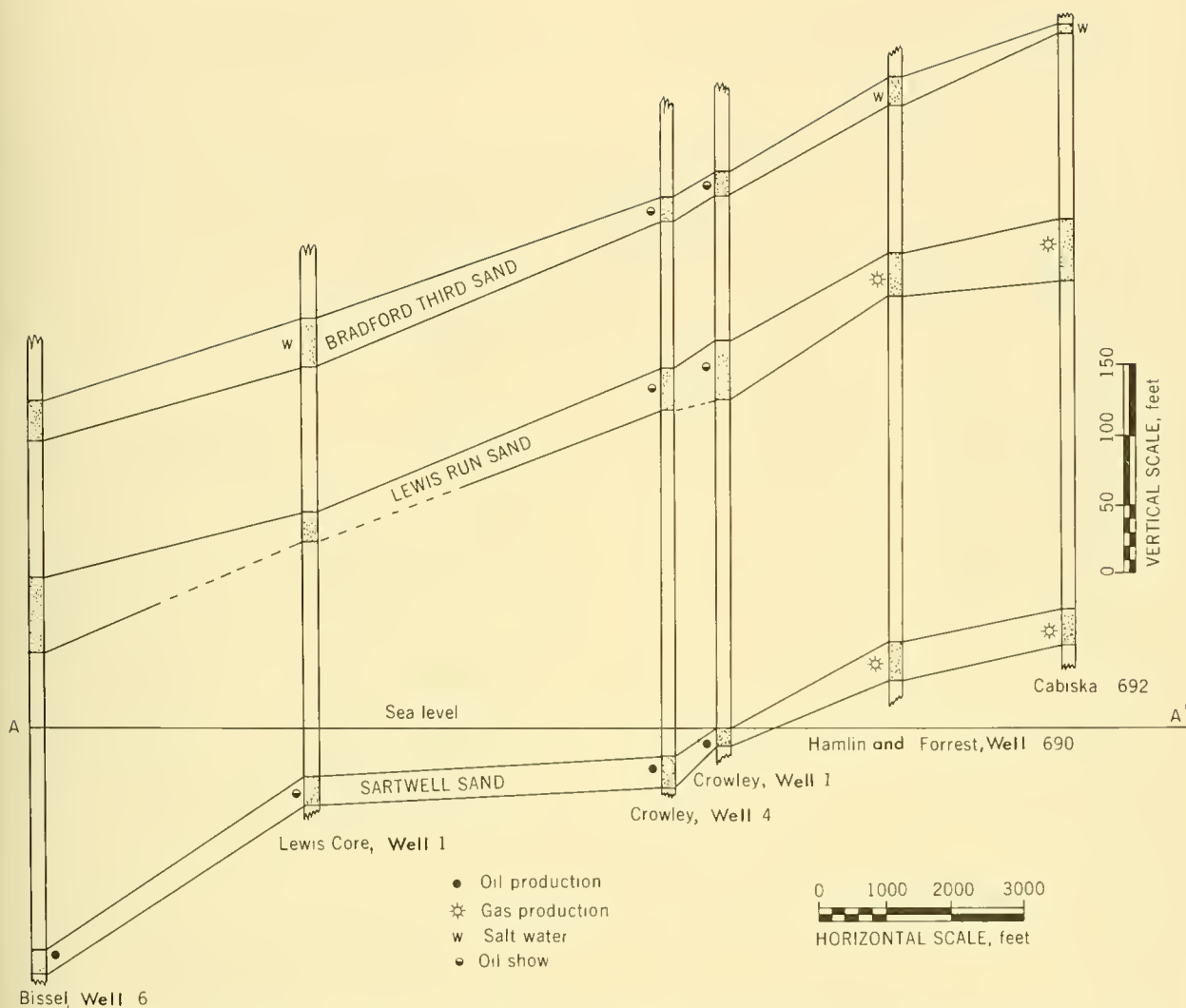
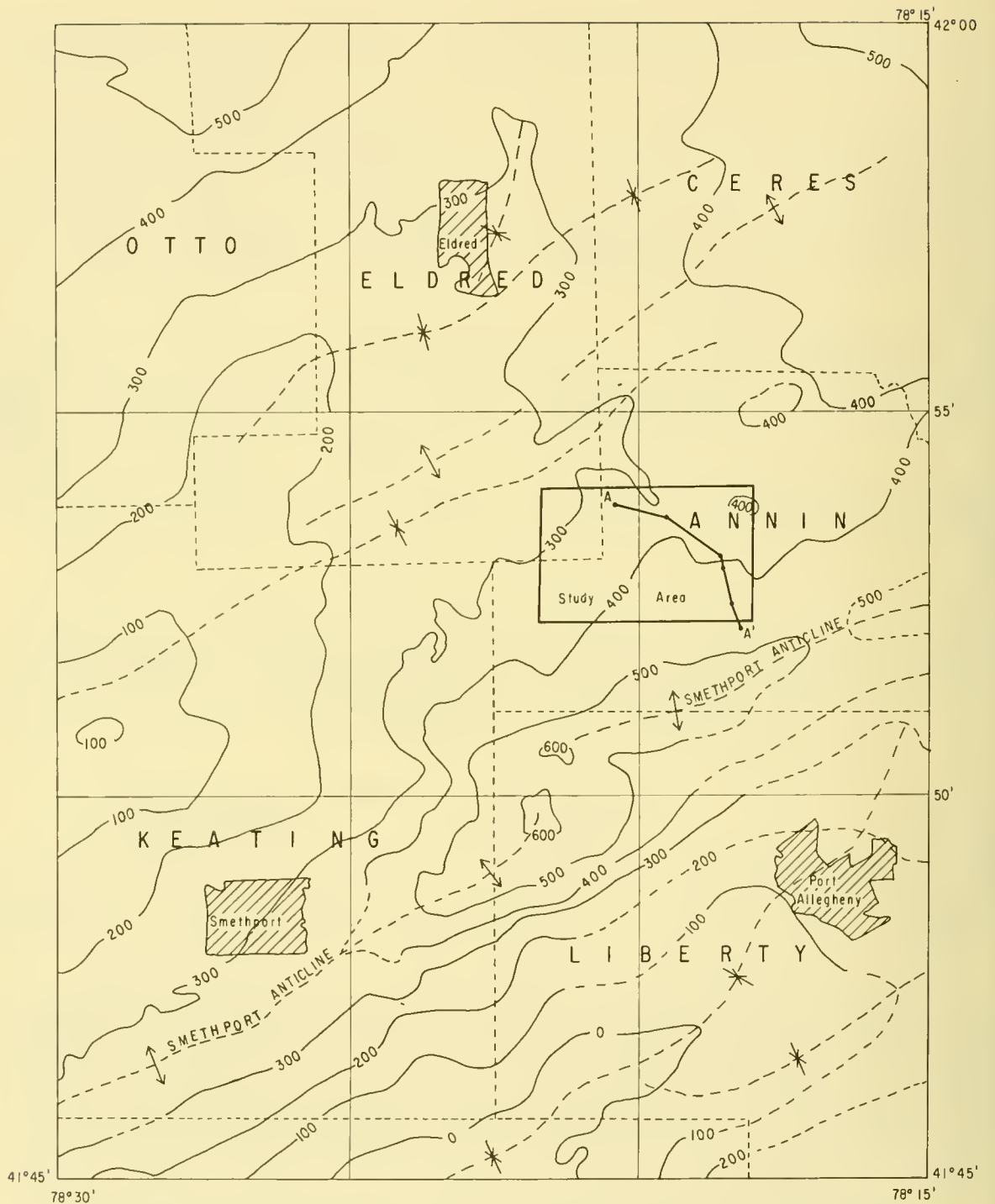


FIGURE 4. - Cross Section Showing Dip and Subsurface Elevations of Sands in the Study Area.

Fettke also noted that the Bradford Third sand is the most persistent of the Canadaway Group, the other sands being "markedly lenticular." Pepper and deWitt (15) concluded that the Canaseraga Sandstone Member of the Perrysburg Formation in southwestern New York was deposited as a subdelta of the large Upper Devonian delta building westward from east central Pennsylvania. They also suggested that the Rushford and Laona Sandstones represent marine fan portions of the subdeltas building westward at the close of deposition of the Perrysburg Formation.

The Bradford Third sand has been correlated with the Richburg sand of Allegany County, N. Y., and its outcrop equivalent, the Rushford Sandstone by Fettke (9), Harding (10), and Pepper and deWitt (15). The conditions of sedimentation outlined by Fettke seems, to the authors, to be readily adaptable to the deltaic or a combination deltaic-littoral depositional environment suggested by Pepper and deWitt.



After SEIFERT, FETKE, and FAIRALL
4th Series
Special Bulletin 6, 1951, PA Geologic Survey

Base From U.S. Geological Survey
Smethport Quadrangle

STRUCTURE CONTOURED ON
TOP OF BRADFORD THIRD SAND
Contour interval = 100 feet

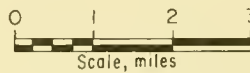


FIGURE 5. - Map Showing Structure of Bradford Third Sand in the Smethport Quadrangle, and the Location of the Study Area, and the Cross Section A-A'.

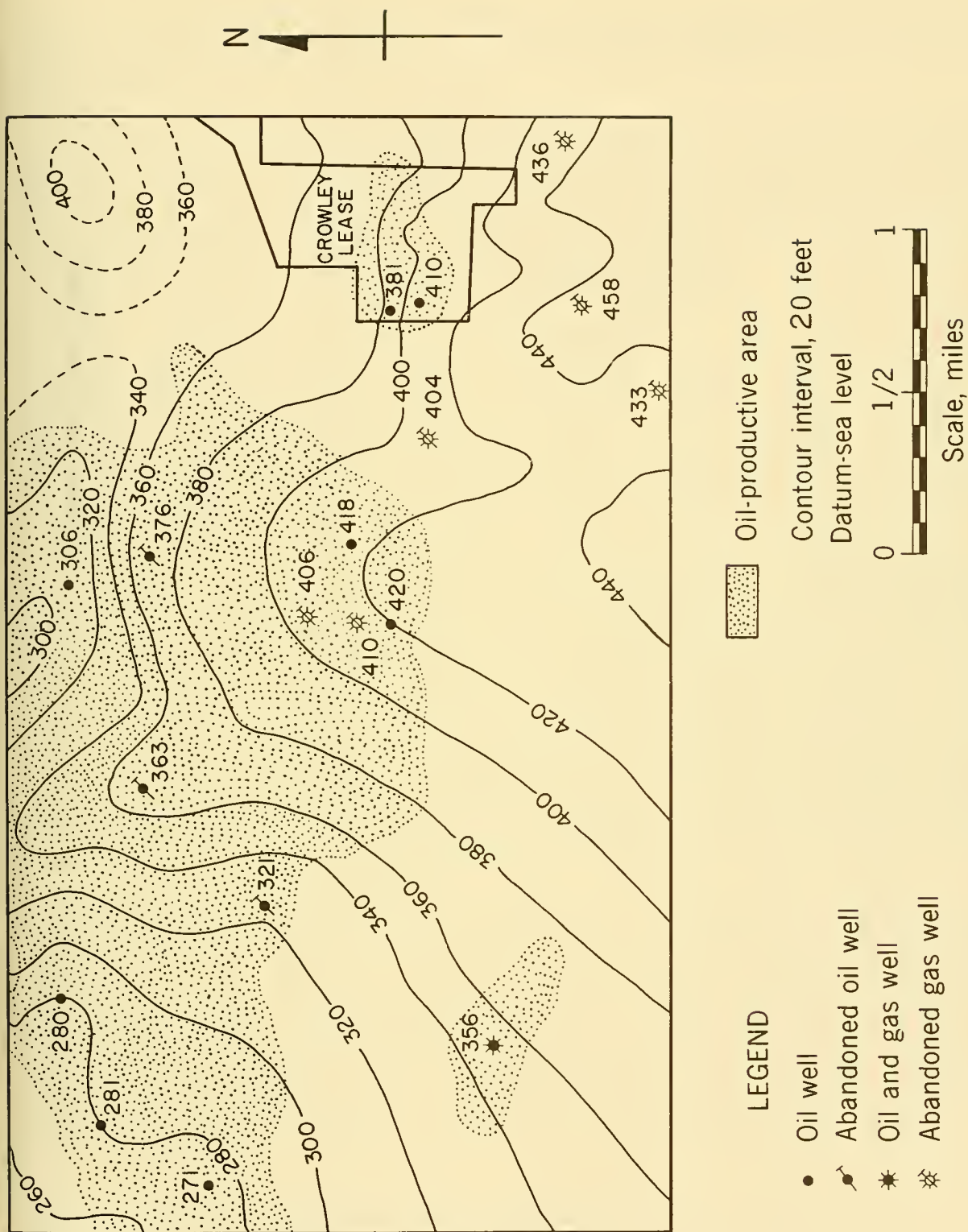


FIGURE 6. - Structure Contoured on Top of the Bradford Third Sand in the Study Area.

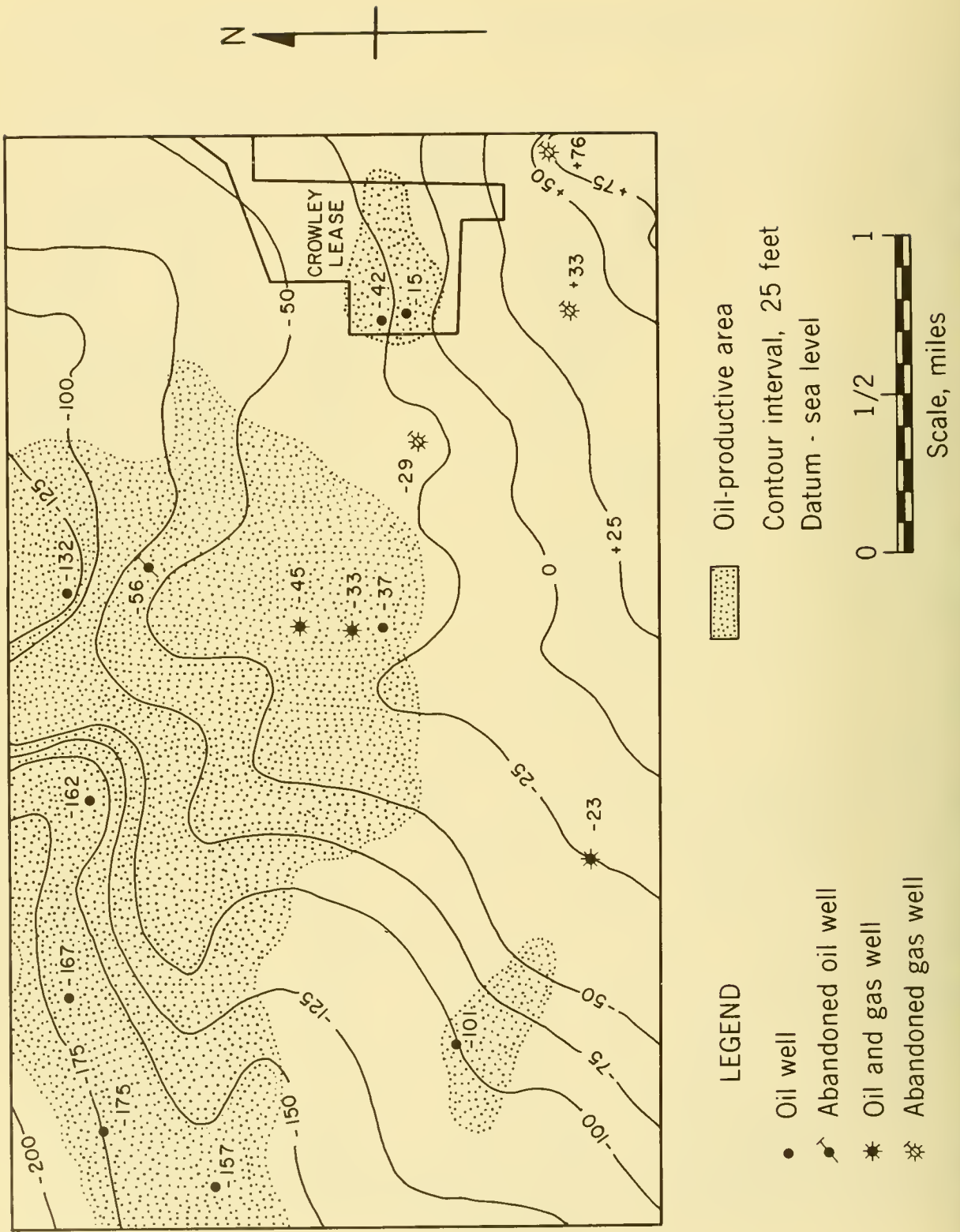


FIGURE 7. - Structure Contoured on Bottom of the Sartwell Sand in the Study Area.

It seems possible that many small streams were building subdeltas from the larger Upper Devonian Delta in a manner similar to the Canaseraga Delta when the Haskill, Sartwell, Kane, and Lewis Run sands were deposited, thus accounting for their lenticular nature.

The Upper Devonian sea apparently oscillated back and forth more often during the deposition of the Haskill, Sartwell, Kane, and Lewis Run sands than when the Bradford Third sand was being deposited. The larger areal extent of the Bradford Third sand seems to indicate that larger streams were active during a period when the sea was more regressive than transgressive. Tidal and longshore currents sorted and redistributed the sands and removed enough silt and clay to allow some sessile forms of marine life to exist.

The longshore currents in sorting and redistributing the sand from the subdeltas were, at the same time, delineating the future reservoir boundaries in these sand bodies. These trends and possibly the direction of the longshore currents may be indicated by the outlines of the old productive areas of, for example, the Sartwell sand (fig. 8). It is assumed that only that section of the sand body with the best reservoir characteristics was productive under the completion practices in use 50 years ago, thus delineating the maximum effect of sizing, sorting, and redistributing by longshore currents.

In general, the isopachous or thickness maps of both the Bradford Third and Sartwell sands (figs 9-10) tend to indicate longshore currents to the southwest as the sand bodies tend to veer off in that direction. Also to be noted is that these trends are outlined by a sand thickness shown by the 30-foot contour. Gamma-ray logs in the study area indicate that when sand thickness exceeding 30 feet is reported on drillers' logs, it is often due to the inclusion of another sand body and the intervening sandy shales that lead to the increased thickness. In some areas, the Sartwell and Lewis Run sands may be 50 feet or more thick, but most of the sand over approximately 30 feet is very argillaceous and very fine-grained with poor reservoir characteristics found at the bottom of the sand body. This section would be typical or representative of the distal portion of a marine fan (fig. 11).

In figure 11, a portion of a hypothetical subdelta is shown where the sediments being carried by the river have formed a marine fan below sea level. Longshore currents have sorted and redistributed the sands in the littoral and sublittoral zones. The gamma-ray curve of the Sartwell sand from a well in the study area has been keyed to the drawing to show the inferred results of lithologies produced by a combination of deltaic and littoral environments. This explanation of the deposition of the graywacke sandstones of the Canada-way Group would account for the lenticular character of the sands and the presence of marine fossils generally in the middle and upper portions of the sand bodies.

If this analysis of the depositional environment is reasonably accurate, the best reservoir characteristics of the sand bodies would follow trends parallel to the ancient shoreline which, during Upper Devonian time, appears to have been northeast-southwest. In the near vicinity of stream mouths, sand grain size would be larger and contribute to better porosity and permeability

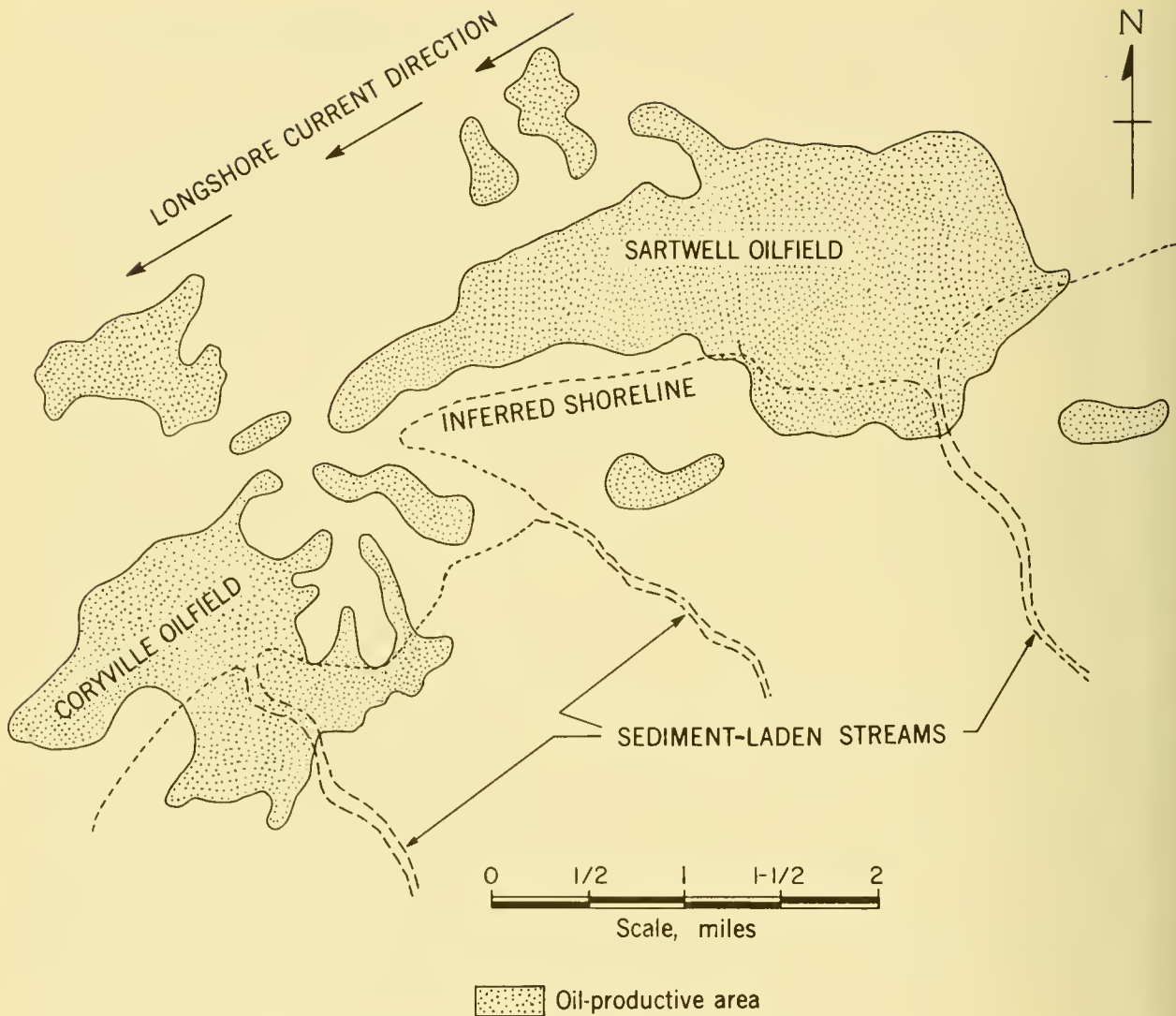
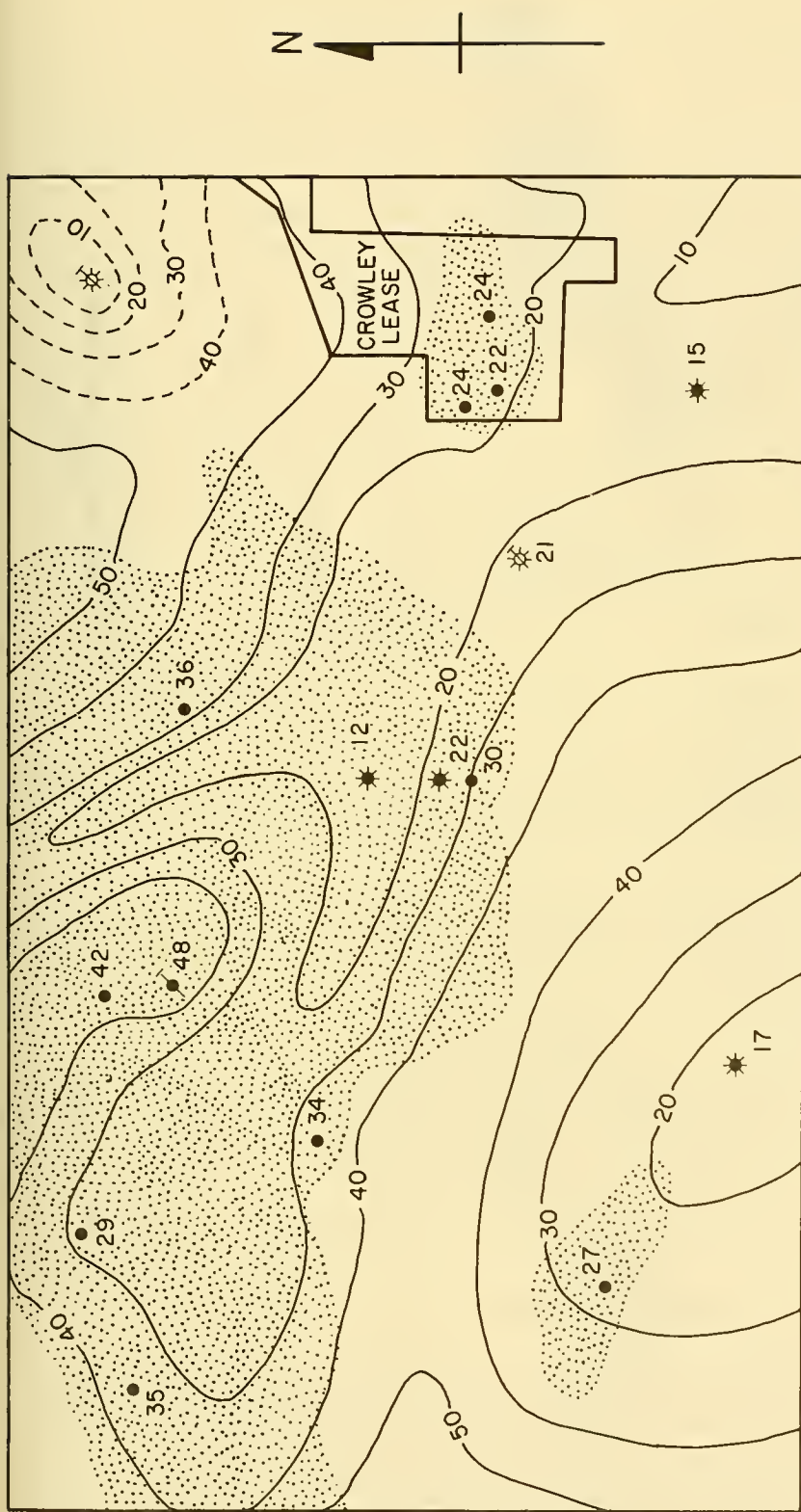


FIGURE 8. - Map Showing Sartwell Sand Oil-Production Areas With Inferred Shoreline and Longshore Current Direction During Deposition of the Sortwell Sand.

than areas to the southwest where grain size would be decreasing. Smaller grain size, more clays, shale stringers, and poorer reservoir characteristics, in general, would be expected in a seaward direction toward the distal portions of the subdeltas. Thus, the reservoir boundaries are most likely controlled by the original depositional environment. The source beds for the petroleum found in these reservoirs were probably the shales being deposited at the same time and adjacent to the sand bodies.

CROWLEY LEASE HISTORY

Three wells were drilled on the Crowley lease (fig. 2) before well 4 was cored and logged by the Bureau. Well 1 was completed in the fall of 1956.



LEGEND

- Oil well
- ⚙ Abandoned oil well
- ★ Oil and gas well
- ⊙ Abandoned gas well

Oil-productive area

Contour interval, 10 feet



Scale, miles

FIGURE 9. - Isopachous Map of the Bradford Third Sand in the Study Area.

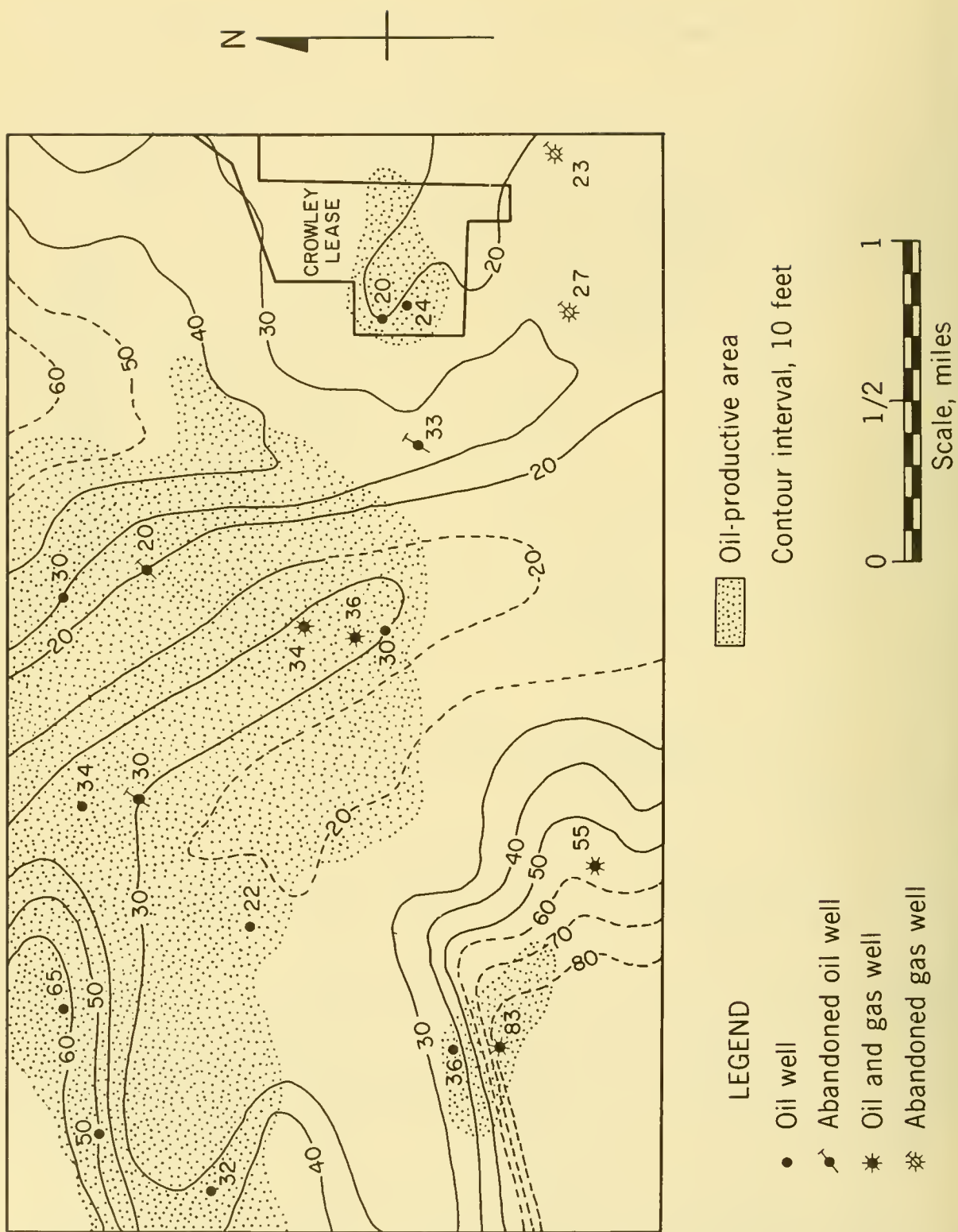


FIGURE 10. - Isopachous Map of the Sartwell Sand in the Study Area.

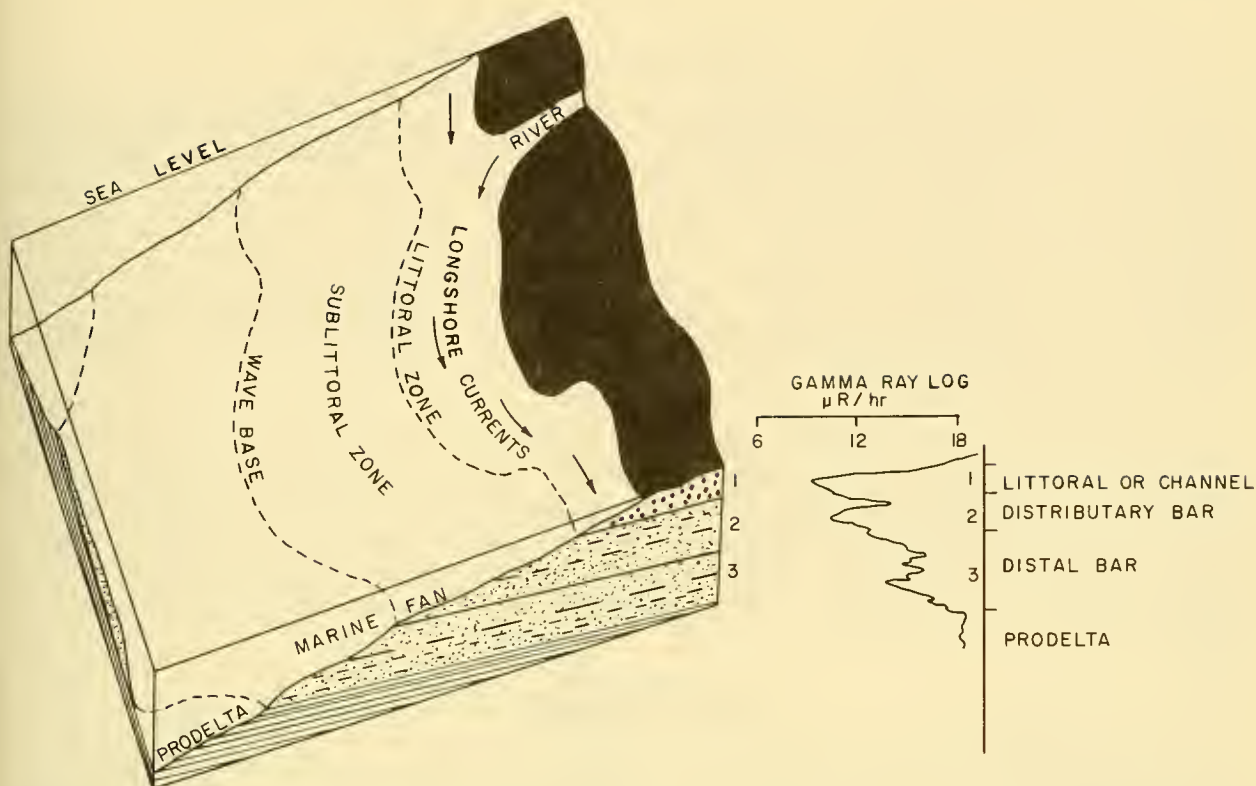


FIGURE 11. - Block Diagram Showing a Gamma Ray Log Keyed to a Portion of a Hypothetical Subdelta of the Type Responsible for Deposition of the Haskill, Sartwell, Kone, and Lewis Run Sands.

The Bradford Third sand was successfully fractured with water but the Sartwell sand did not break down when attempts were made to fracture with water. The Sartwell was then shot, also without success. This well had an initial production of 1 barrel of oil per day.

Well 2, drilled in 1957, was abandoned prior to completion because the production packer was lost and could not be retrieved. Well 3 was completed in the Lewis Run and Sartwell sands in April 1963. The Sartwell sand was shot after both sands in this well failed to respond to an attempted oil fracture.

Total oil production from Crowley wells 1 and 3 to November 1, 1965, was 2,906 barrels.

CORING AND LOGGING

During June and July 1963, the Dewdrop, Bradford Third, Lewis Run, and Sartwell sands were cored with air in Crowley well 4 using a hydraulic power swivel and a 6-1/8-inch-OD by 3-1/2-inch-ID diamond bit. Conventional cable-tool methods were used to drill to a point just above the sand to be cored, then coring operations were initiated and continued through the sand and the top few feet of the underlying strata. This procedure was repeated in coring all four sands. The results are shown in table 1.

TABLE 1. - Schedule of coring operation

Formation	Interval cored		Core recovery, percent	Formation cored			
	Depth, feet ¹			Thickness, feet	Depth, feet ¹		
	From	To			From	To	
Dewdrop.....	682.0	735.6	53.6	66	692.3	709.0	16.7
Bradford Third	1,165.5	1,198.0	32.5	51	1,178.2	1,194.0	15.8
Lewis Run.....	1,293.0	1,339.0	46.0	71	1,299.0	1,327.0	28.0
Sartwell.....	1,571.7	1,602.0	30.3	73	1,580.0	1,596.8	16.8

¹The datum elevation of 1,580.9 feet for depth measurements was the rig floor 2.1 feet above ground level.

After the coring operations were completed, a series of dry- and wet-hole logs were obtained. Dry-hole logs, including gamma ray, neutron, density, temperature, and caliper, were run first. The hole was then filled with a sodium chloride solution (3 lb/bbl of water) and the following wet-hole logs were run: Guard, spontaneous-potential, velocity, gamma ray, neutron, 8- and 16-inch normals, and density. A selected group of these logs is shown in figure 12.

Well Completion

To exclude surface water, 388 feet of 7-inch casing was set in Crowley well 4, then 3-inch tubing was set with a packer at 1,580 feet. The Sartwell sand in this well was then hydraulically fractured through sandjet notches at 1,583 and 1,591 feet. The fracture fluid (17,400 gallons of water and 20,000 pounds of 20- to 40-mesh sand) was injected at an average rate of 19 barrels per minute. Formation breakdown occurred at a pressure of 2,900 psig, and the maximum pressure reached during treatment was 4,300 psig. From results of tracer tests, the operators concluded that no breakdown occurred in the lower zone at 1,591 feet.

Most of the fracture water returned immediately, and the well was equipped to pump with rods through 2-inch tubing set to 1,580 feet. The well began pumping oil within 20 minutes and produced an estimated 39 barrels of 46.2° API gravity crude oil during the first 24 hours. Figure 13 shows estimated daily production and cumulative oil produced to November 1, 1965.

Reservoir Pressure and Temperature

The wellhead pressure in Crowley well 4 was measured in 1963 after fracturing. This pressure (100 psig) was recorded after the liquids in the wellbore had been removed and the well shut-in for 36 hours.

Although a temperature log was run in well 4, the results were discounted as being erroneously high (89° F) because of an overly heated formation which resulted from the air-coring (250° F) medium. The temperature of a nearby well completed in the Bradford Third sand was recorded as 66° F. The reservoir temperatures of the two sands in Crowley well 4 were approximated from the mean areal temperature (46° F) and the geothermal gradient in the vicinity of this well, 0.0143° F/foot (19). Temperatures of 63° F for the Bradford Third

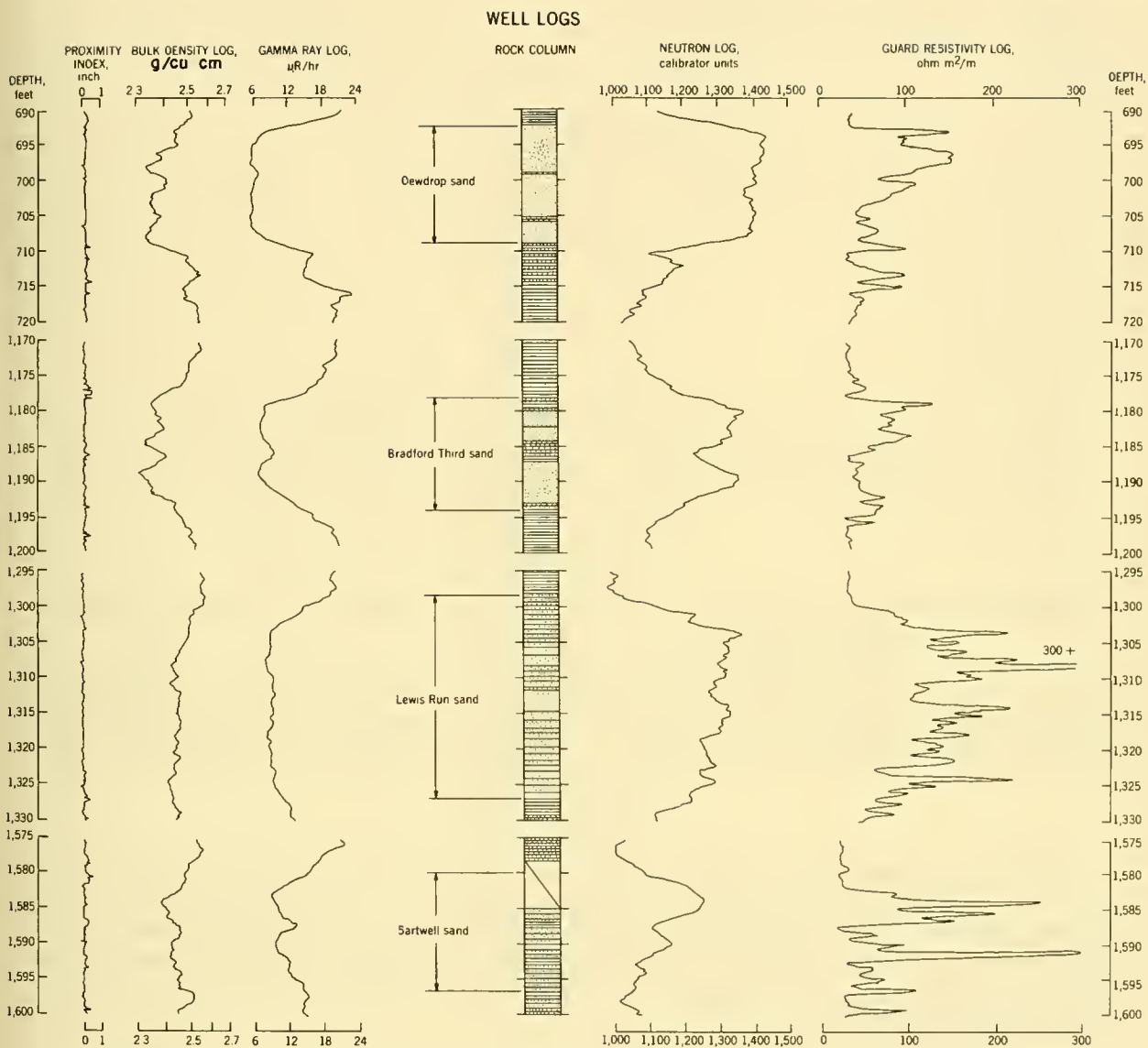


FIGURE 12. - Selected Well Logs of the Dewdrop, Bradford Third, Lewis Run, and Sartwell Sands, Crowley Well 4, Annin Township, McKean County, Pa.

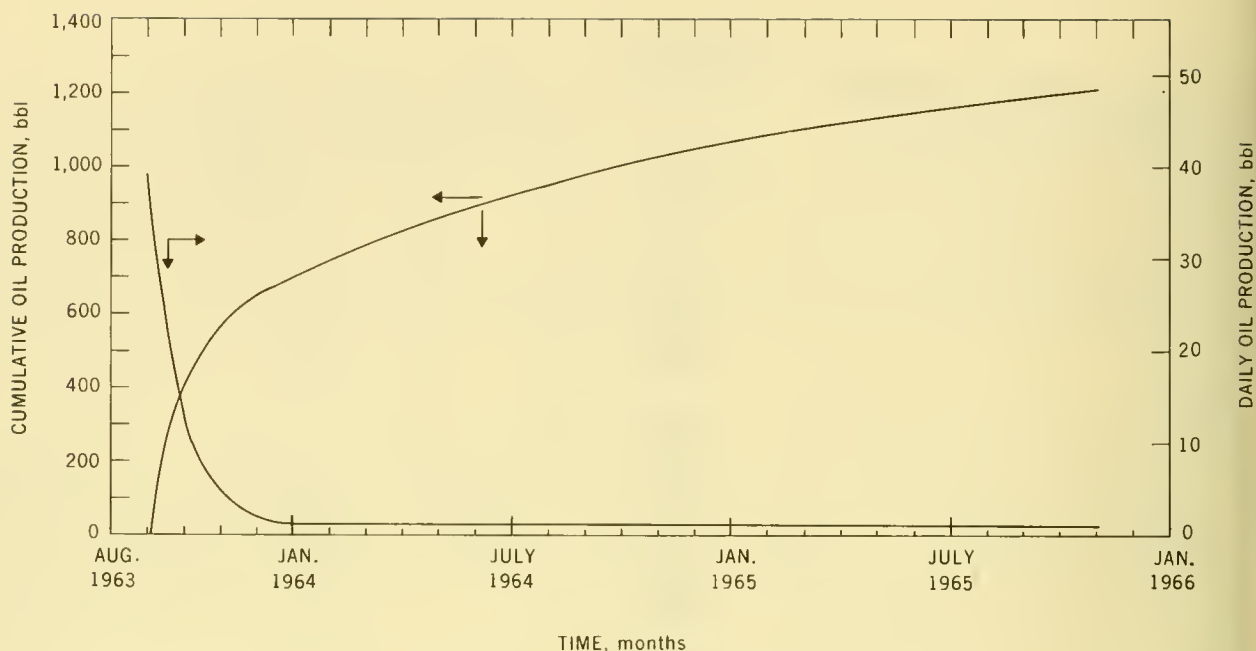


FIGURE 13. - Daily and Cumulative Oil Production From Crowley Well 4, Annin Township, McKean County, Pa.

and 69° F for the Sartwell were computed. Using the same factors and calculation procedure, the computed temperature for the Bradford Third (1,372 feet) in the nearby well was 66° F which is the same temperature recorded by the log.

CORE DATA

Results of the core analysis for Crowley well 4 are shown graphically in figure 14 and the detailed core analysis is presented in table A-1. The Lewis Run and Dewdrop sands average less than 1 millidarcy air permeability and 8 percent porosity and were excluded from further consideration for secondary-recovery processes. Methods of core analysis employed by the Bureau laboratory are described in a previous report (21).

Lithology of Cored Formations

A summary and detailed lithologic description of the cored sands are presented in appendix B.

Clays and Other Minerals

Clay determinations were not performed on the core material by X-ray or differential thermal analysis; however, benzidine stain was used to determine if montmorillonite clays were present. The staining tests did not reveal the presence of any appreciable amounts of montmorillonite clays, therefore the core material was not subjected to water sensitivity tests. Leaching tests similar to those performed by Krynine (11) were conducted with almost identical results, as shown in table 2. It is suggested that the use of a 2-percent

CORE ANALYSIS

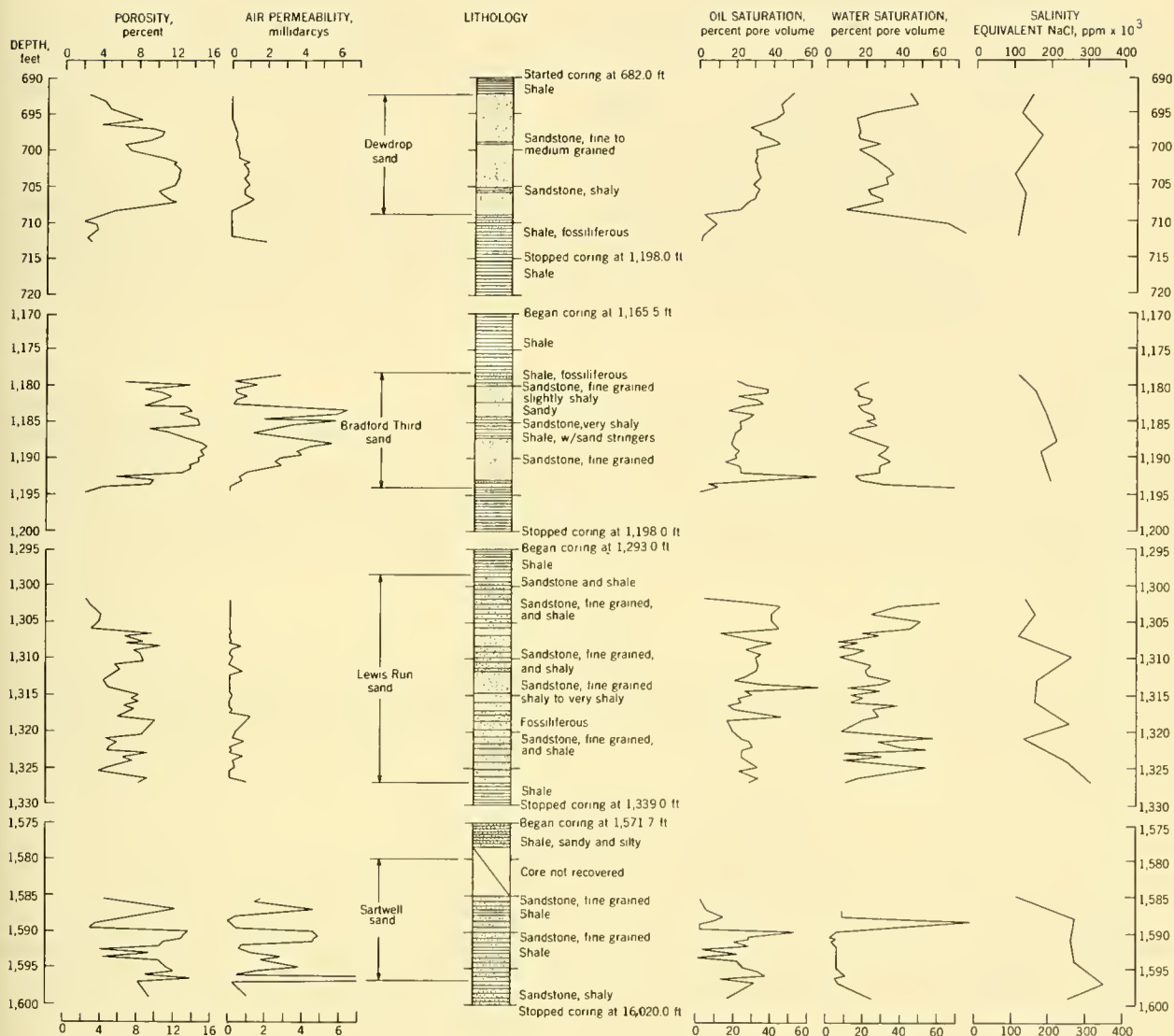


FIGURE 14. - Core Analysis and Formation Lithology of the Dewdrop, Bradford Third, Lewis Run, and Sartwell Sands, Crowley Well 4.

calcium chloride brine solution low in oxygen and containing a bactericide would prevent excess ion exchange reactions with the clays in the sands. This would also suppress the rate of solution of sulfate minerals which could cause the buildup and plugging by gypsum in the producing wells.

Permeability

The effective thickness of the Bradford Third sand was calculated from core analysis to be 14.5 feet. The weighted-average air permeability was 2.8 millidarcys.

TABLE 2. - Soluble minerals leached from Bradford Third sand¹

Elapsed time, hours	Krynine results	Bureau of Mines results
2	95 percent gypsum, 5 percent halite; small crystals.	Not recorded.
24	95 percent gypsum, 5 percent halite; small crystals.	95 percent gypsum, 5 percent halite; small crystals.
48	90 to 95 percent gypsum, 5 percent halite, 2 to 3 percent calcite and dolomite; small crystals.	93 percent gypsum, 5 percent halite, 2 percent calcite and dolomite; small crystals.

¹Distilled water at 25° C.

On the basis of core analysis (appendix A), the top of the Sartwell sand is undefined; however, from well logs, the top of the sand was placed at 1,580 feet. Core material was not obtained from the better section of the Sartwell sand between 1,580 to 1,585 feet. Well-log data in conjunction with core analysis showed the Sartwell Formation to contain 9.3 feet of effective sand with a weighted-average air permeability of 4.7 millidarcys.

Porosity

The average porosity of the effective sand thickness of the Bradford Third was 12.3 percent with a maximum of 15.5 percent as taken from core analysis. The Sartwell effective sand interval had an average porosity of 12.9 percent.

Reservoir-Fluid Saturations

Core analysis indicated that the Bradford Third sand has an average weighted water saturation of 23.0 percent. This value is believed to be fairly representative of the actual water saturation in the formation because the sand was cored with air (3). Core material from the top section of the Sartwell sand was not obtained; therefore, log analysis was used to establish the water saturation which was estimated to be 17.5 percent. There has been no water production from the sands under consideration.

Accurate production data for the area were not available; therefore, the gas saturations were computed from logs. The gas saturations for the Bradford Third and Sartwell sands are estimated to be 16 and 10 percent, respectively. Logs indicate the top 2 feet (1,580 to 1,582) of the Sartwell sand may contain a gas saturation of 30 percent.

Relative Permeability

Representative samples from throughout the Bradford Third and Sartwell sands were subjected to water-oil and gas-oil displacement tests to determine the relative-permeability characteristics of the two sands. Displacement tests were not conducted on the Dewdrop and Lewis Run sands because of their low permeability.

The method of conducting linear water-oil displacement tests on fresh core samples is described in a previous report (2). The average results of two Sartwell and three Bradford Third sand samples are shown in figure 15. Individual test results are shown in table 3.

The relative-permeability characteristics of a porous medium are an indication of its wettability. When the medium is preferentially wet by water, water will flow near the surface of grains and in the smaller pore channels, while oil flow takes place near the center of the larger pores. Because the flow of water in such a system is more restricted than the flow of oil, the relative permeability to oil at irreducible water saturation is greater than

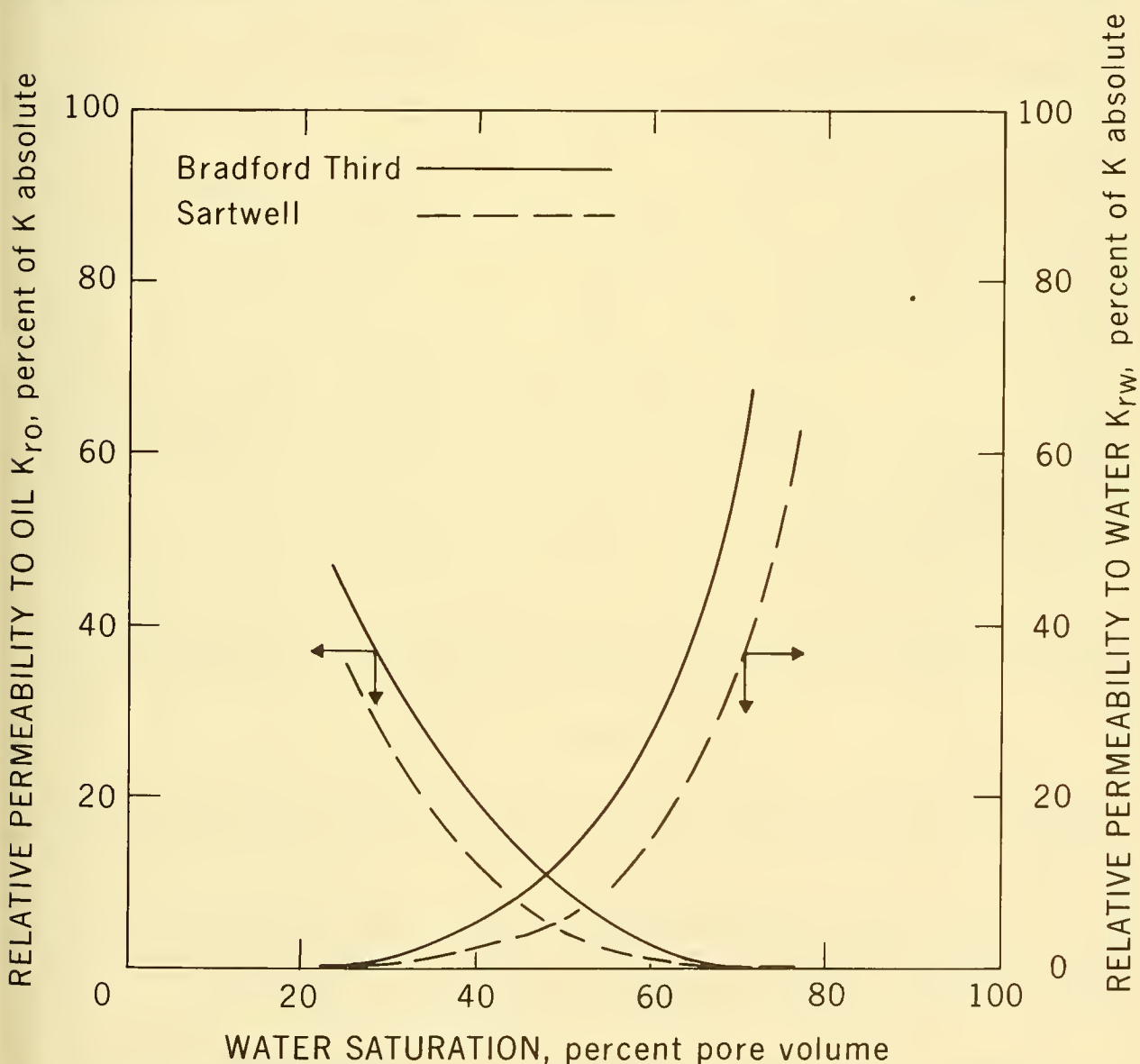


FIGURE 15. - Average Water-Oil Relative Permeability Curves, Crowley Well 4.

the relative permeability to water at residual oil saturation. However, when a porous medium is preferentially oil wet, the reverse is true; oil flows near the grain surfaces and in the smaller pore channels, while water flows in the larger pore channels. The relative permeability to oil at irreducible water in such a porous medium will be lower than the relative permeability to water at residual oil saturation. Figure 15 indicates that both the Bradford Third and Sartwell sands are more oil wet than water wet.

TABLE 3. - Summary of water-oil relative-permeability test results and properties of core samples, Crowley well 4

	Bradford Third sand				Sartwell sand		
	Sample number			Average	Sample number		Average
	1	2	3		4	5	
Irreducible water saturation percent pore volume..	29.9	26.8	13.8	23.5	34.1	15.8	25.0
Effective permeability to oil at irreducible water saturation millidarcys..	1.9	0.5	0.5	1.0	0.2	1.3	0.8
Relative permeability to oil at irreducible water saturation percent..	51.4	33.3	55.6	46.8	16.7	54.2	35.5
Residual oil saturation percent pore volume..	20.4	28.6	37.0	28.7	23.3	23.1	23.2
Effective permeability to water at residual oil saturation millidarcys..	2.8	1.3	0.4	1.5	1.1	0.8	1.0
Relative permeability to water at residual oil saturation percent..	75.7	86.7	44.4	68.9	91.7	33.3	62.5
Depth ¹ feet..	1,183.8	1,185.4	1,191.7	-	1,590.9	1,591.4	-
Porosity.....percent..	14.3	15.3	15.4	15.0	12.8	10.4	11.6
Air permeability.....millidarcys..	5.6	3.2	1.2	3.3	2.4	3.5	3.0
Absolute permeability (Klinkenberg).....do.....	3.7	1.5	0.9	2.0	1.2	2.4	1.8

¹The datum elevation of 1,580.9 feet for depth measurements was the rig floor 2.1 feet above ground level.

Upon completion of the water-oil tests, the samples were cleaned and gas-oil relative-permeability curves obtained using the stationary-phase method proposed by Corey (7). Sample preparation and test procedures are described in another report (21). The average curves for the Sartwell and Bradford Third sands are shown in figure 16.

PREDICTED WATERFLOOD PERFORMANCE

For predicting waterflood behavior, the Sartwell and Bradford Third sands were each considered to be separate, single, homogeneous sands with individual average characteristics. The assumed injection pattern was two adjacent 5-spots on 13.4 acres, as shown in figure 17. Five additional wells would have to be drilled to complete this pattern.

A combination of two different methods was used to predict the waterflood performance of this area. The Suder-Calhoun technique (18) was used to predict the performance up to the time of water breakthrough into the producing wells. After breakthrough, the Craig, Geffen, and Morse technique was used (8). This combination eliminates some of the limitations inherent in each method when used separately.

When using the Craig, Geffen, and Morse technique, a constant average water-injection rate is assumed. However, actual field-flood experiences indicate that the injection rate drops because the resistance to flow increases as the reservoir fills up. The Suder-Calhoun method considers this decrease in water injectivity up to steady-state flow.

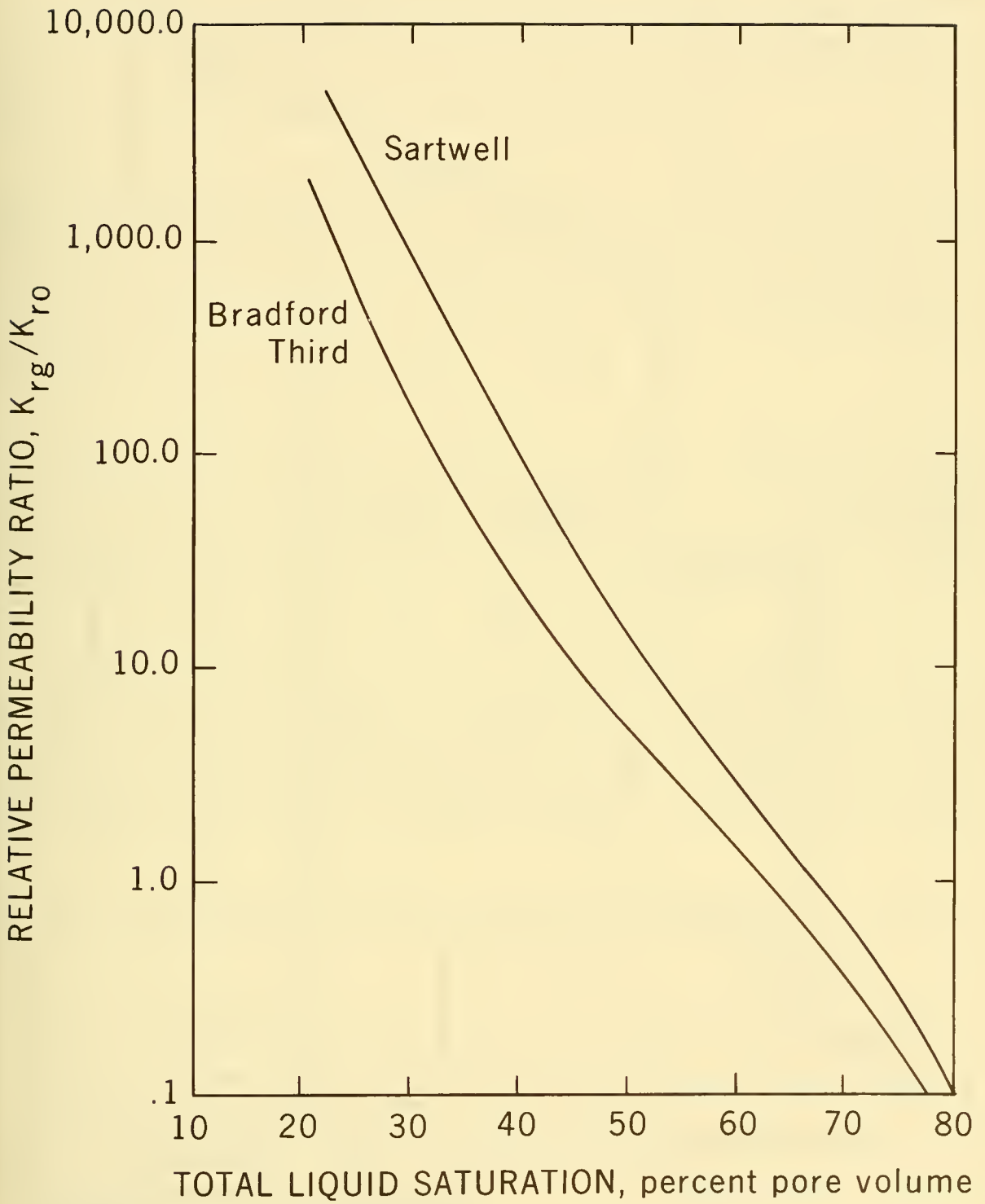


FIGURE 16. - Average Gas-Oil Relative Permeability Ratio Curves, Crowley Well 4.

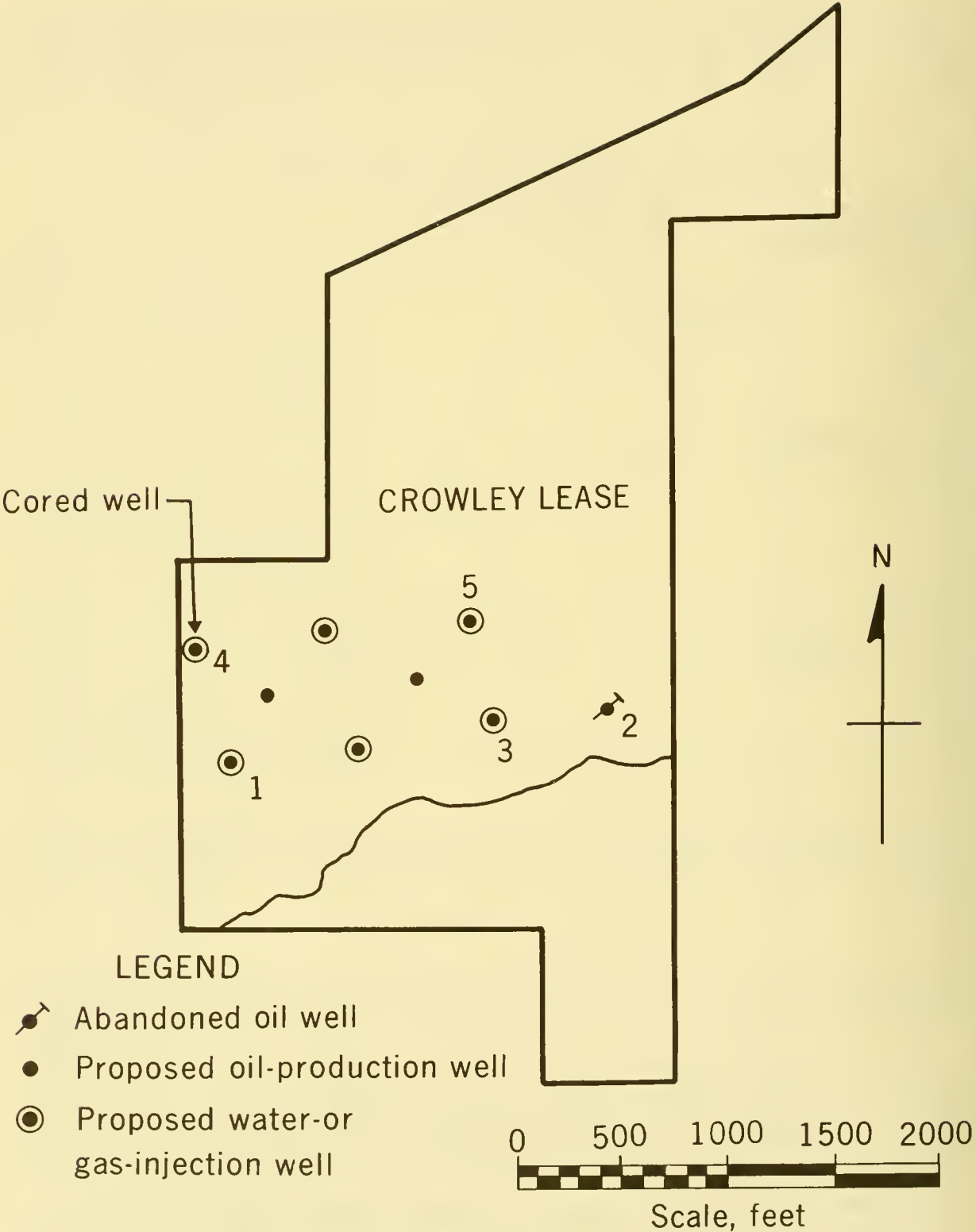


FIGURE 17. - Proposed Flood Pattern for Secondary-Recovery Pilot Project.

Between steady-state flow and water breakthrough, when water is being injected at essentially a constant rate, the Suder-Calhoun technique assumes that oil production from the initially swept area has been pistonlike and complete. Actually, oil is produced by a "drag-type" mechanism at this time (4), and Craig and coworkers consider this additional oil production and also the expanding areal sweep of the water with continued injection.

The predictions obtained through the use of the combined methods are shown in figures 18 and 19. Cumulative oil production (fig. 18) from the Bradford Third sand will approximate 14,500 barrels after 54,000 barrels of water has been injected into this sand within the confined area during a 20-year injection period. The cumulative oil production from the Sartwell sand will be 38,500 barrels after 109,000 barrels of water has been injected into the confined area of this sand over the same period. These cumulative oil-production values are equivalent to 75 and 309 bbl/acre-foot, respectively, for the Bradford Third and Sartwell sands.

Point A on figure 18 indicates the time when oil production will begin in the Sartwell sand after water injection is initiated. This time is denoted as the beginning of steady-state injection in the Suder-Calhoun technique with the modification of the sweep factor. The sweep factor of oil-displacing gas was assumed to be 100 percent before oil production commenced. Point B (fig. 18) indicates the time of water breakthrough into the producing wells for the Sartwell sand. Points C and D refer to the start of oil production and time of water breakthrough, respectively, for the Bradford Third sand flood.

Figure 19 shows the composite predictions for the two reservoirs in the Sartwell oilfield. The start of oil production and the subsequent breakthrough of water in the Sartwell sand are designated by points A and B, respectively, on the cumulative oil-production curve. The rate change at point C reflects the initiation of oil production from the Bradford Third sand. A cumulative oil production of 53,000 barrels (166 bbl/acre-foot) is expected after 163,000 barrels of water has been injected into the pattern area in 20 years.

The data required for a waterflood prediction by the combined (Suder-Calhoun and Craig, Geffen, and Morse) method are shown in table 4. Conditions were as follows:

Pattern to be flooded.....	2 normal 5-spots
Area to be flooded.....	13.4 acres
Distance between injection wells.....	530 feet
Distance between injection and producing wells.....	375 feet
<u>Effective well radius</u> ¹	10 feet

¹Since it is common practice to fracture wells in this region, the effective well radius was assumed to be 10 feet.

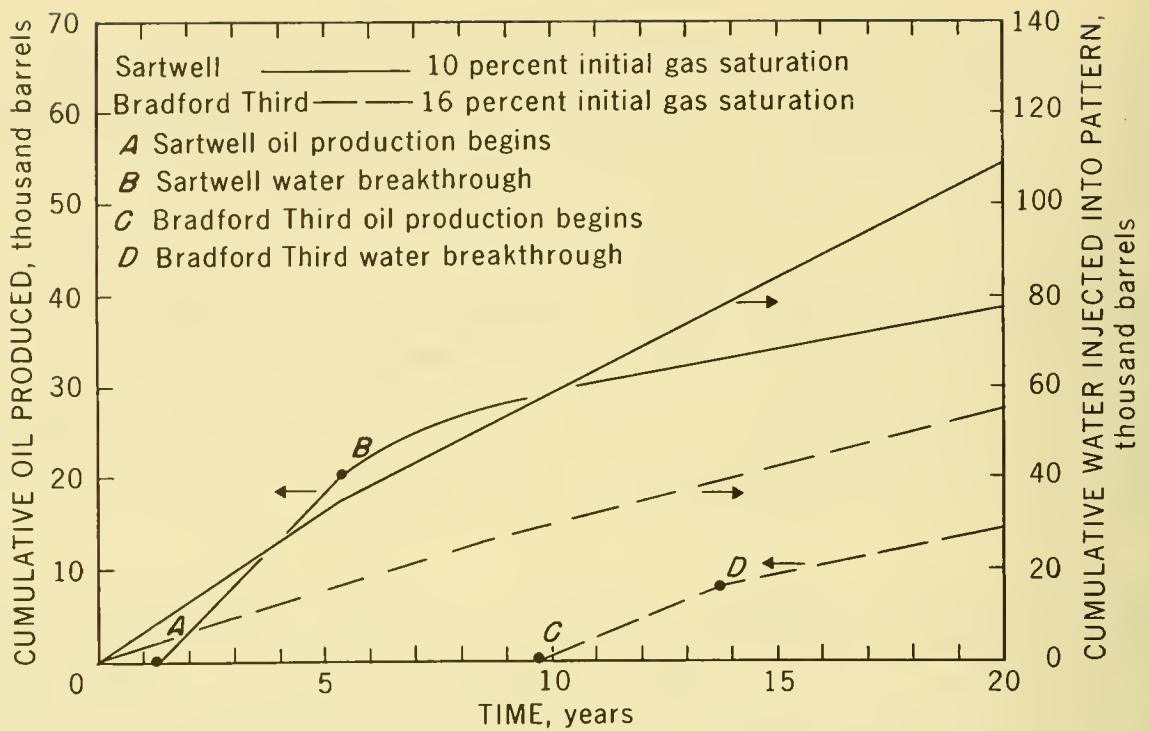


FIGURE 18. - Predicted Cumulative Oil Production and Water Injection for Bradford Third and Sartwell Sands of Proposed Pilot Waterflood.

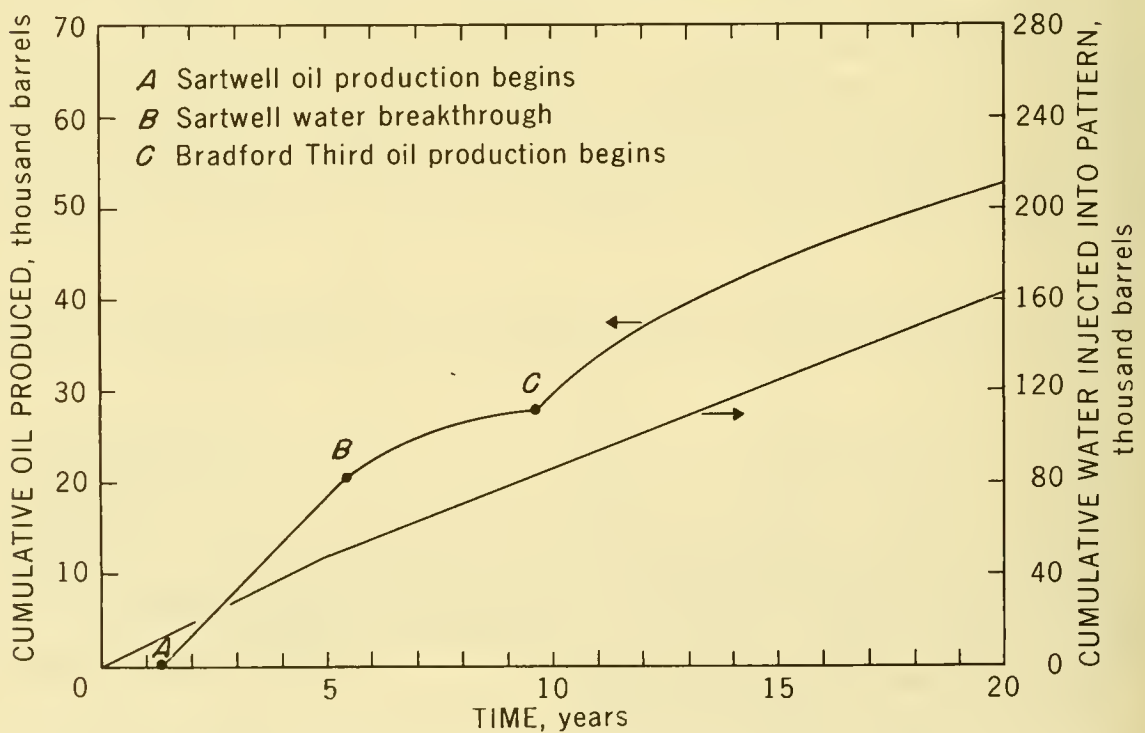


FIGURE 19. - Predicted Cumulative Production and Water Injection for Composite Reservoir of Proposed Pilot Waterflood.

TABLE 4. - Data for waterflood prediction by combined (Suder-Calhoun and Craig, Geffen, and Morse) method

	Bradford Third sand	Sartwell sand
Wellhead pressure ¹ psig..	770	770
Pressure difference between input and producing wells.....psig..	1,190.0	1,360.0
Effective sand thickness.....feet..	14.5	9.3
Average porosity.....percent..	12.3	12.9
Pore volume of confined area.....barrels..	185,400	124,700
Average existing water saturation percent pore volume..	23.0	17.5
Average existing gas saturation.....do.....	16.0	10.0
Average existing oil saturation.....do.....	61.0	72.5
Average permeability to air.....millidarcys..	2.8	4.7
Average water saturation at water breakthrough percent pore volume..	55.0	59.0
Water saturation at passage of stabilized zone percent pore volume..	47.0	53.5
K_{rw} at average water saturation at breakthrough percent..	18.2	13.3
K_{ro} at initial water saturation.....do.....	46.8	35.5
K_{we} at average water saturation at breakthrough millidarcys..	0.3	0.5
Viscosity of water.....centipoise..	1.0	1.0
Viscosity of oil.....do.....	3.367	2.621
Mobility ratio, ² oil to water.....	0.76	1.02

¹An injection wellhead pressure of 770 psig was used to calculate the injectivity of these two sands. This pressure was derived by placing a limiting sand-face pressure of 1 psig per foot of depth on the Bradford Third sand. The bottom-hole hydrostatic pressure at 1,190 feet is 516 psig. This pressure, in addition to the 770 psig wellhead pressure less the reservoir pressure (100 psig), amounts to approximately 1,190 psig or 1 psig per foot of depth on the Bradford Third sand.

²Mobility ratio =
$$\frac{(K_{ro} \text{ at initial water saturation}) (\text{viscosity of water})}{(\text{viscosity of oil}) (K_{rw} \text{ at average water saturation at breakthrough})}$$

PREDICTED GAS-DRIVE PERFORMANCE

The technique proposed by Craig, Geffen, and Morse (8) was used to predict the gas drive performance of the area and the results are shown in figures 20 and 21.

Cumulative oil production and the quantity of gas required to displace this oil from each of the two sands are shown as a function of time in figure 20. The composite performance of the reservoir (fig. 21) shows that about 330 million scf of gas must be injected into the pattern over a period of 20 years to displace about 61,000 barrels of oil (191 bbl/acre-foot).

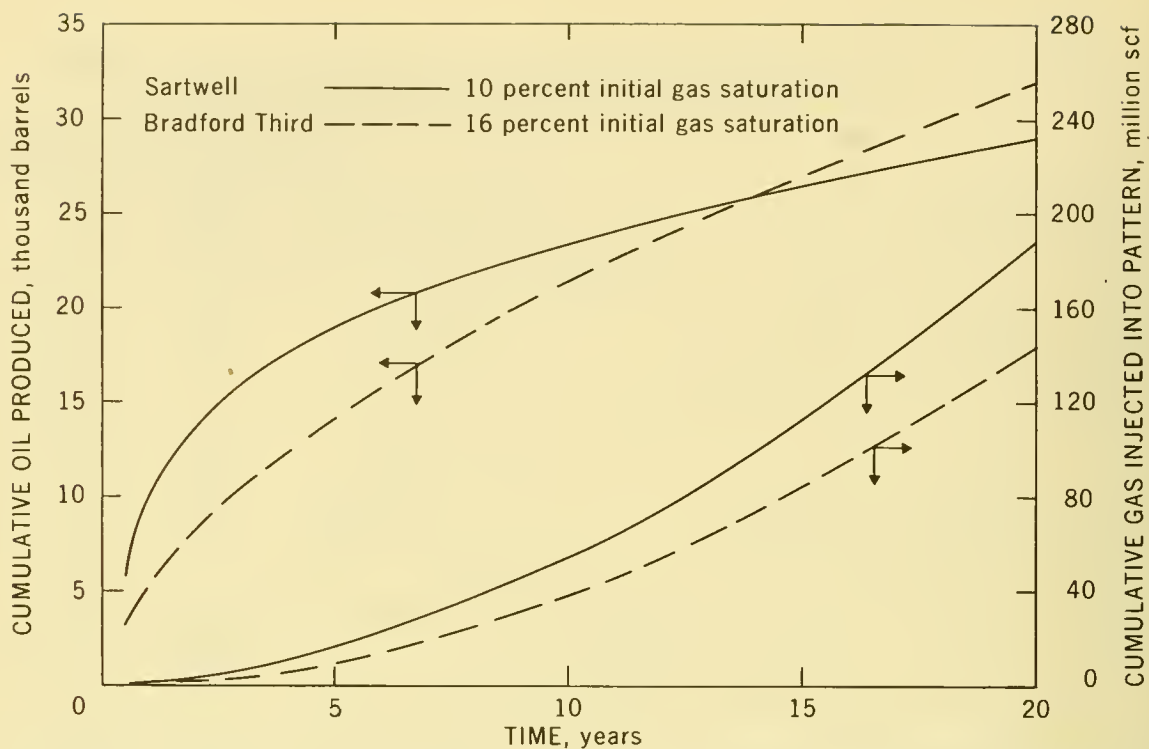


FIGURE 20. - Predicted Cumulative Oil Production and Gas Injection for Bradford Third and Sartwell Sands in Proposed Pilot Gas Drive.

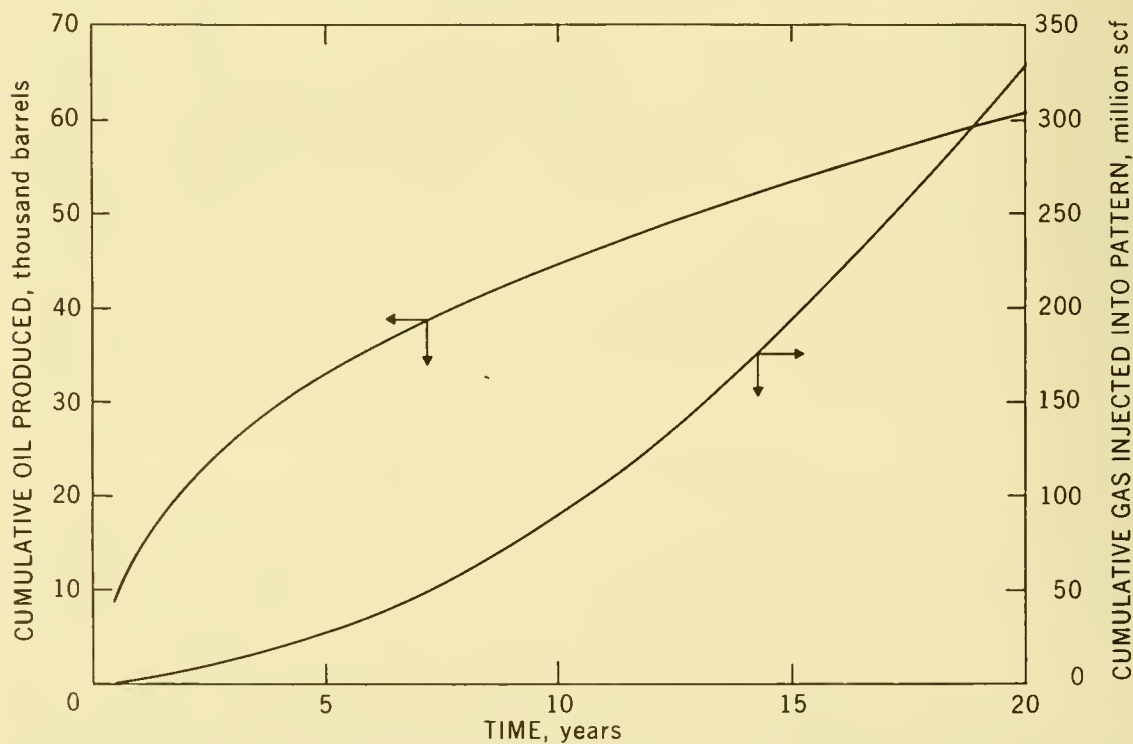


FIGURE 21. - Predicted Cumulative Oil Production and Gas Injection for Composite Reservoir Pilot Gas Drive.

The complete data for a gas drive prediction by the Craig, Geffen, and Morse method are given in table 5. Conditions were the same as for the water-flood prediction.

TABLE 5. - Data for gas drive prediction by the
Craig, Geffen, and Morse method

	Bradford Third sand	Sartwell sand
Wellhead pressure.....psig..	250	250
Pressure difference between input and producing wells.....psig..	190.0	190.0
Effective sand thickness.....feet..	14.5	9.3
Average porosity.....percent..	12.3	12.9
Average existing water saturation percent pore volume..	23.0	17.5
Average existing gas saturation.....do.....	16.0	10.0
Average existing oil saturation.....do.....	61.0	72.5
Pore volume of confined area.....barrels..	185,400	124,700
Average permeability to air.....millidarcys..	2.8	4.7
Average gas saturation at gas breakthrough percent pore volume..	20.6	19.2
Gas saturation at passage of stabilized zone percent pore volume..	20.0	17.5
K_{rg} at average gas saturation at breakthrough percent..	0.03	0.01
K_{ro} at initial gas saturation.....do.....	0.63	0.52
Viscosity of gas.....centipoise..	0.014	0.015
Viscosity of oil.....do.....	3.367	2.621
Mobility ratio, gas to oil.....	0.09	0.28

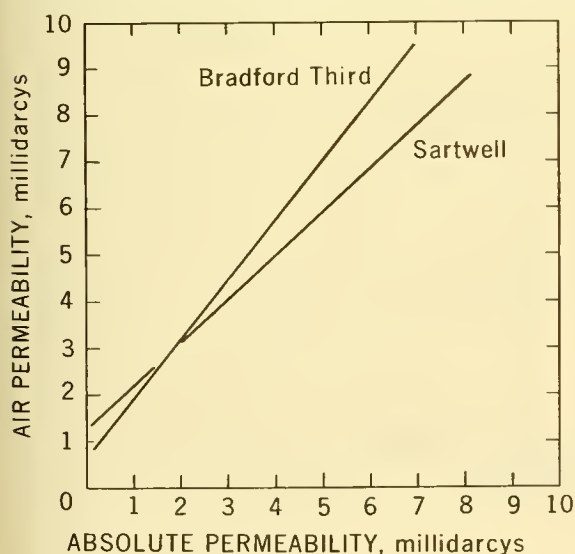


FIGURE 22. - Correlation Between Air and
Absolute Permeabilities for the Brad-
ford Third and Sartwell Sands.

INJECTIVITY

In Appalachia and other areas in which the absolute permeability of the sand is low, the injection rate is a matter of prime economic interest. In such areas, the injection pressure is set at some predetermined value and held constant while the rate is allowed to vary with time. The injection pressure is usually a function of sand depth with a convenient rule of thumb being 1 pound per square inch per foot of depth (17).

The absolute permeabilities of the Bradford Third and Sartwell sands of this field are quite low as are the air permeabilities. A correlation between the air and absolute permeabilities from laboratory tests conducted on samples from these sands is shown in figure 22.

Based on consideration of the applicable injection pressure and the fact that the absolute permeability is quite low, one can see that the calculated theoretical injection rates from Darcy's radial flow equation (18), as presented in the article by Suder-Calhoun, will be quite low. An example for the Bradford Third sand follows: Limiting the sand-face pressure to 1 pound per square inch per foot of depth on the Bradford Third fixes a pressure differential of 1,190 psig on this sand. From figure 22, the absolute permeability that corresponds to the average air permeability of 2.8 millidarcys is found to be 1.7 millidarcys. From figure 15, the relative permeability to water at the average water saturation in the reservoir at water breakthrough is found to be 0.182. The effective permeability to water at this saturation is then

$$K_w = (K_{abs})(K_{rw}),$$

where

K_w = effective permeability to water, millidarcys,
 K_{abs} = absolute permeability (Klinkenberg), millidarcys,
 and K_{rw} = relative permeability to water, percent,

so that

$$K_w = (1.7)(0.182) = 0.31 \text{ millidarcys.}$$

Suder-Calhoun present the following formula to describe the steady-state rate of injection into a formation:

$$Q = \frac{0.00154 K_w h \Delta P}{\mu \left(\log \frac{W}{r_w} - 0.420 \right)},$$

where

K_w = effective permeability to water = 0.31 millidarcy,
 h = sand thickness = 14.5 feet,
 ΔP = pressure difference between sand face and reservoir = 1,190.0 psig,
 μ = viscosity of water = 1.0 centipoise,
 W = distance between injection wells = 530 feet,
 and r_w = effective well radius after fracture, assumed, 10 feet,

so that

$$\begin{aligned} Q &= \frac{(0.00154)(0.31)(14.5)(1,190)}{1.0 \left(\log \frac{530}{10} - 0.420 \right)} \\ &= 7.6 \text{ bbl/day/well.} \end{aligned}$$

This injection rate is the steady-state rate and is the minimum value. The rate of injection into a reservoir usually varies with time, with the

maximum at the beginning of injection and quickly decreasing to a steady-state value as the pressure gradient in the reservoir decreases.

DISCUSSION OF RESULTS

There are two principal requirements for a successful gas drive or water-flood operation. The reservoir must contain a commercial quantity of mobile oil and the injection rate into the formation must be sufficient to permit economic oil-production rates.

The limited data available from the Crowley lease indicate that enough mobile oil exists in the reservoir. In addition, the measured gas-oil and water-oil relative permeability characteristics are favorable and will aid the displacement process. However, the rate of injection of water and/or gas into the Sartwell and Bradford Third sands, as indicated by the low absolute permeabilities, seems to be unfavorable. From the available laboratory data and the assumptions stated, it appears the rate of injection of fluid into these sands will be a factor of prime importance when considering secondary recovery of oil from this field.

Stimulation of the injection wells in the proposed pattern by fracturing would undoubtedly increase the injection rates in this area and thereby decrease the time element required to produce the predicted results. However, the predictions are considered to be reasonable in this area when the injection wells are unstimulated. The present low injection capacity is the principal reason why either waterflooding or gas drive is expected to recover about 53,000 to 61,000 barrels of oil (166 to 191 bbl/acre-foot) over a period of 20 years.

CONCLUSIONS

The Bradford Third and Sartwell sands in the Sartwell oilfield appear to have sufficient mobile oil to warrant secondary-recovery operations. However, the injection rate into these sands must be sufficiently high to produce this oil in a reasonable length of time. From laboratory tests, the injectivity characteristics appear to be unfavorable.

Since the economic rate of return for each operator is different, the economics of a specific secondary-recovery project must be evaluated by that operator. Such an evaluation should be made prior to the injection of a fluid in this area, and should include the cost of drilling and completing the additional five wells assumed to be part of the injection pattern. If the economics appear to be favorable, the reservoir should be further evaluated by injecting gas into well 4 to test the in situ injectivity, and coring and logging additional wells (at least proposed well 5, fig. 17) to determine if the reservoir properties are continuous within the project area.

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APPENDIX A

TABLE A-1. - Core-analysis results, Crowley well 4

Depth, feet	Air permeability, millidarcys	Porosity, percent	Fluid saturation, percent pore volume		Salinity, equivalent NaCl, ppm ¹
			Oil	Water	
Dewdrop Sand					
692.3	<0.1	2.0	50.9	43.7	154,000
693.3	-	2.4	-	-	-
693.8	<.1	3.4	44.3	48.1	-
694.3	<.1	4.3	-	-	-
695.0	-	6.2	44.8	23.8	122,000
695.8	<.1	8.5	41.4	14.9	-
696.4	-	3.4	-	-	-
697.0	.2	9.6	26.9	16.2	-
697.7	.3	10.8	33.4	17.4	-
698.0	.3	10.7	32.3	16.4	177,000
698.6	.2	9.2	38.6	17.4	-
699.2	.3	6.4	44.1	27.5	-
700.1	.4	7.2	31.4	16.2	-
701.1	.4	10.8	30.6	23.5	134,000
701.7	1.0	12.2	29.6	27.3	-
702.0	.7	11.8	31.3	28.8	-
702.7	.9	12.4	30.7	31.7	-
703.4	.9	12.2	31.9	34.7	104,000
703.9	.7	11.8	33.4	30.7	-
704.8	1.0	11.4	29.0	31.8	-
705.6	.7	10.3	31.8	20.6	-
706.1	.7	10.4	31.0	22.3	132,000
706.8	1.2	11.5	29.7	28.6	-
707.2	1.0	12.2	26.8	29.0	-
708.3	<.1	5.1	22.1	8.1	-
709.0	-	1.9	1.8	-	122,000
710.2	-	3.4	9.1	63.5	-
711.6	-	3.5	2.8	74.4	-
712.0	<.1	2.4	1.9	-	112,000
712.7	2.0	2.9	1.0	-	-
Average	.6	7.8	28.2	29.6	132,000
Bradford Third Sand					
1178.5	2.9	-	-	-	113,000
1179.0	-	-	-	-	-
1179.5	.2	6.7	21.4	22.9	-
1180.0	1.5	13.4	26.3	17.7	-
1180.6	.3	8.6	38.4	14.3	-
1181.0	.4	10.6	37.7	17.2	163,000
1181.5	1.0	11.8	22.4	17.4	-
1182.0	.4	10.8	31.8	23.7	-
1182.6	.2	8.8	35.1	21.7	-
1182.9	2.7	13.1	24.0	15.9	-
1183.5	6.4	13.9	16.3	18.5	-
1184.0	5.9	12.5	29.8	23.8	190,000
1184.7	1.8	14.5	25.5	24.8	-

See footnote at end of table.

TABLE A-1. - Core analysis results, Crowley well 4--Continued

Depth, feet	Air permeability, millidarcys	Porosity, percent	Fluid saturation, percent pore volume		Salinity, equivalent NaCl, ppm ¹
			Oil	Water	
Bradford Third Sand--Continued					
1185.0	5.7	14.6	21.6	20.8	-
1185.5	3.3	14.8	23.4	26.9	-
1186.0	-	9.2	22.6	16.3	-
1186.6	1.2	11.6	19.9	11.5	-
1187.6	-	-	-	-	219,000
1188.0	5.5	15.0	18.3	26.6	-
1188.5	4.3	15.5	19.5	32.8	-
1189.1	3.6	14.8	21.7	31.4	-
1189.6	3.8	15.2	20.2	27.2	-
1190.1	2.7	14.5	21.2	30.7	175,000
1190.6	2.4	14.6	15.1	34.0	-
1191.0	2.8	13.6	21.9	29.4	-
1191.5	1.7	13.7	23.0	27.8	-
1192.0	.9	12.8	23.4	27.6	-
1192.6	.5	5.6	63.9	15.4	-
1193.1	.7	9.8	30.5	17.7	202,000
1193.6	.4	9.3	5.0	29.6	-
1194.0	<.1	4.2	11.5	68.8	-
1194.7	<.1	2.3	1.4	-	-
Average	2.2	11.6	23.9	24.7	177,000
Lewis Run Sand					
1301.8	<0.1	2.4	3.3	-	137,000
1302.5	<.1	2.8	28.4	60.1	-
1303.0	<.1	3.2	45.2	37.7	-
1304.0	<.1	4.1	39.6	23.9	162,000
1305.0	<.1	3.9	39.9	50.8	-
1306.0	<.1	3.0	44.2	45.1	-
1306.7	.1	9.8	12.2	18.9	-
1307.0	<.1	6.6	17.5	29.2	115,000
1307.8	.1	8.8	32.5	6.4	-
1308.0	<.1	6.9	41.4	16.8	-
1308.5	.7	10.6	31.7	6.5	-
1309.0	.1	7.6	26.0	20.8	-
1309.6	<.1	8.5	35.3	15.0	-
1310.0	.2	8.8	32.2	6.4	259,000
1311.0	<.1	5.6	33.3	23.6	-
1311.7	-	6.3	32.2	20.7	-
1312.0	.8	5.7	26.9	21.8	-
1312.5	<.1	4.9	20.1	35.1	-
1313.0	<.1	4.4	34.3	30.0	166,000
1314.0	<.1	4.9	66.4	11.4	-
1314.5	<.1	6.8	24.8	29.0	-
1315.0	.2	8.4	30.4	12.6	-
1315.5	.1	7.4	21.9	19.8	-
1316.0	<.1	8.3	23.5	13.1	161,000
1316.5	<.1	6.5	16.7	38.7	-

See footnote at end of table.

TABLE A-1. - Core-analysis results, Crowley well 4--Continued

Depth, feet	Air permeability, millidarcys	Porosity, percent	Fluid saturation, percent pore volume		Salinity, equivalent NaCl, ppm ¹
			Oil	Water	
Lewis Run Sand--Continued					
1317.0	0.2	7.8	20.4	25.0	-
1318.0	<.1	5.8	45.7	28.4	-
1318.5	1.2	10.0	15.7	19.5	-
1319.0	-	-	-	-	255,000
1320.0	.4	8.5	18.9	7.9	-
1321.0	.2	4.5	23.8	57.2	129,000
1321.4	.9	5.9	27.8	27.4	-
1322.2	<.1	5.0	30.4	38.6	-
1322.6	.2	4.7	25.0	54.2	-
1323.0	<.1	9.4	23.7	10.9	-
1323.5	.8	6.3	24.1	30.0	-
1324.0	.2	7.7	27.1	8.8	246,000
1325.0	.3	4.7	32.8	54.1	-
1325.5	<.1	3.8	21.7	-	-
1326.0	-	-	-	-	-
1326.5	.1	9.2	32.6	16.3	-
1327.0	.0	8.3	27.7	10.0	312,000
Average	.2	6.4	28.9	25.8	194,000
Sartwell Sand					
1585.0	-	-	-	-	110,000
1585.5	1.8	4.5	2.5	-	-
1586.0	1.4	-	-	-	-
1587.0	4.6	12.4	5.4	8.9	-
1588.0	.4	7.4	14.7	8.7	270,000
1588.6	<.1	4.9	10.2	76.7	-
1589.0	-	3.5	2.5	-	-
1589.6	.4	3.0	2.0	-	-
1590.0	4.6	13.8	52.8	6.0	-
1590.7	4.9	13.1	28.2	2.2	-
1591.0	4.7	13.0	29.0	5.9	260,000
1591.4	4.6	11.0	20.9	3.0	-
1592.0	.7	10.6	28.6	5.7	-
1592.5	.6	4.0	2.8	-	-
1593.0	1.2	9.4	23.0	6.0	-
1593.6	2.9	4.3	1.1	-	-
1594.0	1.8	10.4	22.0	5.7	270,000
1595.0	3.9	11.3	25.7	5.8	-
1595.5	1.5	12.1	33.0	7.7	-
1596.0	.5	8.9	37.7	10.6	-
1596.4	20.8	14.0	12.8	4.9	-
1597.0	.2	8.2	31.7	6.5	350,000
1598.2	-	-	-	-	-
1599.0	1.0	9.4	16.6	23.7	252,000
Average	3.0	9.0	19.2	11.8	252,000

¹Core-water salinity determined by leaching crushed core sample with distilled water, measuring water resistivity and converting to equivalent NaCl.

APPENDIX B.--SUMMARY OF LITHOLOGIC DESCRIPTION

The following is a summary of the lithologic description of the Dewdrop, Bradford Third, Lewis Run, and Sartwell sands.

Dewdrop Sand

The Dewdrop sandstone is light brown, fine to medium grained (0.125 to 0.250 mm), micaceous, slightly calcareous (carbonate present mostly as dolomite and ankerite), and shaly. The matrix material is clay (mostly finely divided particles of illite, sericite, biotite, and muscovite micas), and occupies 5 to 10 percent of the rock volume. Quartz grains are angular, glassy to white, frequently elongated, poorly sorted, and occupy 75 to 85 percent of the rock volume. The remaining 10 to 15 percent of the rock volume is occupied by shale, dolomite, and ankerite (frequently in rhombohedral crystals 0.25 to 0.50 mm in length), muscovite, and biotite mica. Small amounts of feldspar and chlorite are also present.

In portions of the core (692.0 to 697.0 feet), secondary recrystallization of dolomite and ankerite in the pore space has reduced porosity and permeability.

Throughout the core, 50 to 75 percent of the pore-wall space is lined with clay. This apparently does not adversely affect porosity except in areas where the matrix material exceeds 7 percent of the rock volume.

In the core description, the sandstone is described as dolomitic, but a large percentage of the carbonate material present is ankerite $\text{CaCO}_3(\text{Mg, Fe, Mn})\text{CO}_3$ and exhibits the same rhombohedral cleavage as dolomite $\text{CaMg}(\text{CO}_3)_2$. Ankerite was detected during the core examination by the rather rapid, deep purple coloring assumed by the crystal during staining with 0.1 percent sodium alizarate solution (Alizarine Red S).

Bradford Third Sand

The Bradford Third sandstone is medium to dark (chocolate) brown, fine grained (0.10 to 0.25 mm), micaceous, slightly calcareous (carbonate present mostly as dolomite and ankerite, and disseminated throughout the matrix material), shaly, and fossiliferous in streaks. The matrix material is clay (mostly finely divided particles of illite, sericite, biotite, and muscovite micas), with some carbonate material (dolomite-ankerite) present, and occupies 5 to 10 percent of the rock volume. The sand grains are angular, glassy to light gray, frequently elongated, poorly sorted quartz grains, and occupy 80 to 90 percent of the rock volume. The remaining 5 to 10 percent is occupied by shale, fossils, and mica. The shale is micaceous and light gray in color. Muscovite and biotite mica are found as detrital flakes (0.2 to 0.5 mm).

Porosity of the sandstone is intergranular, with clay lining 50 to 75 percent of the pore-wall space.

The fossils are composed of calcite crystals (rhombohedral), sometimes replaced by dolomite. Fossils are mostly brachiopods (spirifers), but a few pelecypods were noted.

In the core description, the sandstone is described as dolomitic, but a large percentage of the carbonate material present is ankerite.

Lewis Run Sand

The Lewis Run sandstone is light to medium brown, fine grained (0.12 to 0.25 mm), slightly dolomitic, micaceous, and argillaceous. It contains many clay and shale partings and is often fossiliferous (mostly spirifer brachiopods). The matrix material is a finely divided mica clay which occupies 5 to 20 percent of the rock volume. The sand grains are light gray to glassy, angular, often elongated, poorly sorted quartz grains, and occupy 80 to 90 percent of the rock volume. The remaining 5 to 10 percent is occupied by light gray shale, muscovite and biotite mica (detrital flakes 0.15 to 0.45 mm), dolomite, and ankerite.

Porosity of the sandstone is intergranular, with clay lining 50 to 75 percent of the pore-wall space.

Sartwell Sand

The Sartwell sandstone is light to dark brown, fine grained (0.09 to 0.25 mm), micaceous, slightly calcareous (some small zones 5 to 10 mm thick, quite limy) and dolomitic (carbonate present as dolomite and ankerite), and contains several shale partings. The mica clay matrix material loosely but firmly bonds the clear to light gray, angular quartz grains. The sand grains are frequently elongated, poorly to fairly well sorted, and occupy 85 to 90 percent of the rock volume. Clay and shale compose the remaining 10 to 15 percent of the rock. The shale partings are light gray, micaceous, and fossiliferous (mainly spirifer brachiopods).

The porosity in this sand is intergranular, and is generally higher throughout than that of the Dewdrop, Bradford Third, and Lewis Run because of the lower clay content (2 to 10 percent).

Approximately 30 to 50 percent of the pore-wall space is clay lined compared with 50 to 75 percent for the Dewdrop, Bradford Third, and Lewis Run sandstones. Because of the amount of matrix material present, all of the cored sands could be described as low-rank graywacke sandstones.

TABLE B-1. - Detailed lithologic description
of Crowley well 4

(Intervals designated as missing were removed for laboratory tests)

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Dewdrop Sand			
682.0	683.0	1.0	Shale; medium-gray, finely micaceous, laminated, plant fossils.
683.0	684.0	1.0	Shale; medium-gray, finely micaceous, laminated, plant fossils.
684.0	685.0	1.0	Shale; medium-gray, finely micaceous, contains small specks (0.05 to 0.10 mm) of carbonaceous material.
685.0	688.0	3.0	Shale; medium-gray, finely micaceous, laminated; some laminations are light gray in color.
688.0	692.0	4.0	Shale; medium-gray; finely micaceous, laminated, small specks of carbonaceous material, very slightly calcareous near bottom.
692.0	692.3	.3	Shale; medium-gray, slightly micaceous, sandy; becoming a shaly, dolomitic sandstone from 692.2 to 692.3. Bottom zone contains fossil fragments of crinoid stems, columns, and pieces of pelecypod shells. Sandstone is light gray, fine to medium (0.25 to 0.5 mm), glassy, subangular quartz grains, poorly sorted.
692.3	692.5	.2	Sandstone; light-gray, fine to medium (0.25 to 0.5 mm), quartzitic, glassy, subangular quartz grains, poorly sorted. Sand grains rather loosely but rigidly bonded by matrix material (clay and dolomite), composing 7 to 10 pct of rock volume; considerable (5 pct) amount of dolomite-ankerite crystals (rhombohedral) scattered throughout; sand is oil stained.
692.5	692.9	.4	Missing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Dewdrop Sand - Continued			
692.9	693.3	0.4	Sandstone; grayish-brown, fine-grained matrix, shaly, argillaceous, micaceous, dolomitic, many dolomite crystals (2.0 mm to 6.0 mm in length), slightly fossiliferous (dolomite replacement). Quartz grains are fine to coarse size, light-gray, to glassy, angular, poorly sorted. Some grains partially leached.
693.3	693.7	.4	Missing.
693.7	694.3	.6	Sandstone; grayish-brown, fine-grained, shaly, dolomitic. Matrix, consisting of mica, clay, and dolomite, occupies approximately 10 percent of rock volume. Quartz grains are white to light gray, angular to subangular, slightly leached, poorly sorted, traces of subhedral quartz. Oil stained.
694.3	694.7	.4	Missing.
694.7	695.1	.4	Sandstone; light-brown, fine- to medium-grained, shaly, micaceous, dolomitic. Matrix material is clay, and silt to clay size quartz particles with small amounts of dolomite (7 pct of rock volume). Quartz grains are clear and glassy, angular (10 to 20 pct may be subhedral quartz), poorly sorted. Oil stained.
695.1	695.4	.3	Missing.
695.4	696.4	1.0	Sandstone; light-brown, fine-grained (0.125 mm to 0.160 mm), shaly, dolomitic. Matrix material is clay (appears to be decomposed mica) detrital mica, and dolomite (matrix 10 pct of rock volume). Dolomite has replaced calcite in fossil crinoid column plates (some pyrite replacement also). Quartz grains are glassy, subangular and some show partial leaching; poorly to fairly well sorted. Some scattered medium and coarse grains, traces of chert, pyrite, and gypsum. Oil stained.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Dewdrop Sand - Continued			
696.4	696.8	0.4	Missing.
696.8	697.5	.7	Sandstone; light-brown, fine grained (0.13 mm to 0.16 mm), micaceous, slightly dolomitic. Matrix material composed mainly of mica and clay (matrix 10 to 15 pct of rock volume). Quartz grains are glassy, subangular, poorly sorted. Considerable amount of detrital biotite mica. Traces of chlorite. Oil staining spotty.
697.5	697.9	.4	Missing.
697.9	698.2	.3	Sandstone; light-brown, fine-grained (0.13 mm to 0.16 mm), micaceous, slightly dolomitic. Matrix material composed mainly of mica and clay (matrix 10 to 15 pct of rock volume). Quartz grains are glassy, subangular, poorly sorted. Considerable amount of detrital biotite mica. Traces of chlorite. Oil staining spotty.
698.2	698.5	.3	Missing.
698.5	699.5	1.0	Sandstone; light-brown, fine-grained, shaly, micaceous, slightly calcareous and dolomite. Matrix material; clay (5 to 9 pct of rock volume). Quartz grains are glassy, subangular, poorly sorted. Dolomite crystals (0.3 mm to 0.5 mm) indicate primary porosity reduced by recrystallization of dolomite in many pore spaces. Shale is in thin layers near bottom. Oil stained.
699.5	699.8	.3	Missing.
699.8	700.7	.9	Sandstone; light-brown, fine-grained, shaly, micaceous, dolomitic. Matrix material composed of clay, silt, and mica (5 to 10 pct of rock volume). Dolomite and mica apparently present as both detrital and matrix material. Sand

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Dewdrop Sand - Continued			
			grains are glassy, angular to subangular, quartz (0.12 mm to 0.25 mm), poorly sorted. Small lenses of carbonaceous material. Pyritic replacement of pieces of wood partially carbonized. Oil stained.
700.7	701.0	.3	Missing.
701.0	701.2	.2	Sandstone; light-brown, fine-grained, micaceous, Matrix material; clay (5 pct of rock volume). Quartz is glassy, angular, poorly sorted, oil stained.
701.2	701.6	.4	Missing.
701.6	702.0	.4	Sandstone; light-brown, fine-grained (0.10 mm to 0.25 mm), micaceous. Matrix material; clay (5 pct of rock volume). Quartz is glassy, angular, poorly sorted. Oil stained.
702.0	702.3	.3	Missing.
702.3	703.0	.7	Sandstone; light-brown, fine-grained, micaceous, dolomitic. Matrix material; clay (5 to 7 pct of rock volume). Quartz grains are glassy, angular (0.12 mm to 0.25 mm), poorly sorted. Traces of chlorite, feldspar. Oil stained.
703.0	703.5	.5	Sandstone; light-brown, fine-grained, micaceous, slightly dolomitic. Matrix material; clay (10 to 15 pct of rock volume). Quartz grains are white, some glassy, angular to subangular (0.12 to 0.25 mm), poorly sorted. Oil stained.
703.5	703.8	.3	Missing.
703.8	704.3	.5	Sandstone; light-brown, fine-grained, micaceous, slightly dolomitic. Matrix material; clay (10 to 15 pct of rock volume). Quartz grains are white, some glassy, angular to subangular (0.12 to 0.25 mm), poorly sorted. Oil stained.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Dewdrop Sand - Continued			
704.3	704.6	0.3	Missing.
704.6	705.2	.6	Sandstone; light-brown, fine-grained, micaceous, slightly dolomitic. Matrix material; clay (5 pct of rock volume). Small inclusions of light-green waxy shale. Mica is both biotite and muscovite, plates show rounding. Quartz grains are white, some glassy, angular (0.12 to 0.25 mm) poorly to fairly well sorted. Specks of carbonaceous material. Oil stained.
705.2	705.5	.3	Missing.
705.5	706.3	.8	Sandstone; light-gray and light-brown, fine-grained, shaly, slightly micaceous, slightly dolomitic. Matrix material; clay (5 pct of rock volume). Quartz grains are glassy, poor to fairly well sorted. Oil stained.
706.3	706.7	.4	Missing.
706.7	707.3	.6	Sandstone; light-brown as above, except containing more mica; muscovite predominating over biotite. Small, waxy, light-green shale inclusions. Oil stained.
707.3	708.0	.7	Missing.
708.0	708.5	.5	Sandstone; light-brown, fine-grained, slightly calcareous and dolomitic, micaceous. Quartz grains are angular, glassy, poor to fairly well sorted. Matrix material; clay (5 pct of rock volume).
708.5	708.7	.2	Missing.
708.7	709.6	.9	Shale; greenish-gray, micaceous, silty and sandy, fossiliferous, brachiopod casts, crinoid columns, fish bones, bryozoa fragments.
709.6	710.0	.4	Missing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Dewdrop Sand - Continued			
710.0	710.8	0.8	Shale; light-gray, silty, sandy in zones, slightly micaceous, calcareous, dolomitic, very fossiliferous; crystalline calcite and dolomite have replaced fossils. Some pyrite replacements. Fossils; mostly crinoid columns and brachiopod shells.
710.8	711.2	.4	Missing.
711.2	711.4	.2	Shale; light-gray, silty, sandy in zones, slightly micaceous, calcareous, dolomitic, very fossiliferous; crystalline calcite and dolomite have replaced fossils. Some pyrite replacements. Fossils; mostly crinoid columns and brachiopod shells.
711.4	711.6	.2	Missing.
711.6	712.2	.6	Shale; medium-gray, finely micaceous, soft.
712.2	712.4	.2	Missing.
712.4	712.8	.4	Shale; medium-gray, finely micaceous.
712.8	715.6	2.8	Shale; medium-gray, finely micaceous.
715.6	735.6	20.0	Shale; not examined.
Bradford Third Sand			
1178.2	1179.0	.8	Shale; light-gray, very finely micaceous.
1179.0	1179.5	.5	Shale; light-gray, very finely micaceous, fossiliferous, sandy, silty. (Sand shale contact 1179.5).
1179.5	1179.8	.3	Missing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Bradford Third Sand - Continued			
1179.8	1180.4	0.6	Sandstone; medium- to dark-brown, fine-grained, slightly calcareous and dolomitic, slightly micaceous, thin streaks of light-gray argillaceous material. Matrix material is clay (finely divided particles of muscovite, seracite, and biotite micas), approximately 2 to 5 pct of rock volume. Quartz grains are glassy, angular (0.125 to 0.250 mm), poorly sorted. Oil Stained. Porosity intergranular.
1180.4	1180.6	.2	Missing.
1180.6	1181.2	.6	Sandstone; as above, except fossiliferous and shaly in streaks. Pyritized wood, carbonaceous specks and streaks. Fossils are crystalline calcite and dolomite replacement of brachiopods and crinoid columns. Oil stained.
1181.2	1181.4	.2	Missing.
1181.4	1182.3	.9	Sandstone; medium- to dark-brown, fine-grained (0.125 to 0.250 mm), slightly shaly and micaceous, slightly dolomitic, fossiliferous. Matrix material; clay (5 pct of rock volume). Quartz is glassy, angular, poorly sorted and oil stained.
1182.3	1182.5	.2	Missing
1182.5	1183.0	.5	Sandstone; dark-brown, as above.
1183.0	1183.3	.3	Missing.
1183.3	1183.9	.6	Sandstone; medium- to dark brown, fine-grained (0.125 to 0.250 mm), shaly, micaceous, slightly dolomitic, fossiliferous (mostly brachiopod shells). Matrix material is clay (5 to 7 pct of rock volume). Quartz is glassy, angular, poorly sorted, and oil stained. Alternating zones (1/2" to 1" thick) of medium- to dark-brown sandstone. Darker sand carries more organic matter, shale partings, and mica. Bedding planes have thin layers of clay and mica, and readily permit fracturing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Bradford Third Sand - Continued			
1183.9	1184.4	0.5	Sandstone; medium- to dark-brown, fine-grained, slightly micaceous, slightly shaly, slightly dolomitic, fossiliferous (mostly calcite replaced brachiopod shells). Matrix material is clay (5 to 7 pct of rock volume). Quartz grains are glassy to light gray, angular, poorly sorted (0.10 to 0.17 mm). Light oil stain.
1184.4	1184.6	.2	Missing.
1184.6	1185.0	.4	Sandstone; medium-brown, fine-grained, micaceous, dolomitic, Matrix material is clay (5 pct of rock volume). Quartz grains are glassy to light gray, angular, poorly sorted (0.10 to 0.17 mm). Light oil stain.
1185.0	1185.6	.6	Sandstone, as above.
1185.6	1185.9	.3	Missing.
1185.9	1186.1	.2	Sandstone; medium-brown, fine-grained, slightly calcareous and dolomitic, very shaly, fossiliferous (spirifer brachiopods mainly). Matrix material is clay and silt (5 to 10 pct of rock volume). Quartz grains are white to glassy, angular, poorly sorted (0.125 to 0.250 mm). Light oil stain. Shale is light greenish-gray.
1186.1	1186.3	.2	Missing.
1186.3	1186.6	.3	Sandstone; as above.
1186.6	1187.0	.4	Shale; light-gray, slightly silty and sandy. Sand stringers 8 to 10 mm thick.
1187.0	1187.2	.2	Shale; light-gray, micaceous.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Bradford Third Sand - Continued			
1187.2	1187.8	0.6	Sandstone; medium- to dark-brown, fine-grained, micaceous, fossiliferous (brachiopods and pelecypods), dolomitic, Matrix material is clay (5 to 10 pct of rock volume). Mica is detrital, muscovite, and biotite, edges somewhat rounded. Quartz grains are white to light-gray, angular (0.12 to 0.20 mm), and poorly sorted.
1187.8	1188.7	.9	Sandstone; medium- to dark-brown, fine-grained, micaceous, slightly dolomitic, shaly and fossiliferous in streaks. Matrix material is clay (5 to 7 pct of rock volume). Muscovite and biotite detrital mica. Quartz grains are light-gray to glassy, angular (0.125 to 0.250 mm), and poorly sorted. Shale streaks are light gray. Oil stain.
1188.7	1189.0	.3	Missing.
1189.0	1189.3	.3	Sandstone; medium- to dark-brown, fine-grained, micaceous, dolomitic, Same as above except no shale streaks.
1189.3	1189.6	.3	Missing.
1189.6	1190.7	1.1	Sandstone; medium- to light-brown, fine-grained, slightly micaceous and dolomitic. Matrix material is clay (5 to 7 pct of rock volume). Quartz is glassy to light-gray, angular (0.12 to 0.25 mm), and poorly sorted. Slight oil stain.
1190.7	1190.9	.2	Missing
1190.9	1191.1	.2	Sandstone; as above except little or no mica present.
1191.1	1191.4	.3	Missing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Bradford Third Sand - Continued			
1191.4	1192.2	0.8	Sandstone; medium-brown, fine-grained, micaceous, slightly dolomitic, slightly fossiliferous. Matrix material is clay (5 to 10 pct of rock volume). Mica is detrital muscovite. Quartz is light gray, angular (0.12 to 0.20 mm), and poorly sorted.
1192.2	1192.5	.3	Missing.
1192.5	1193.0	.5	Sandstone; light-gray to light brown, very fine-grained, argillaceous, slightly dolomitic, micaceous. Matrix material is clay and mica (10 to 20 pct of rock volume). Quartz is light gray, angular (0.07 to 0.12 mm), and poorly sorted.
1193.0	1193.3	.3	Shale; light-gray, very finely micaceous.
1193.3	1193.5	.2	Missing.
1193.5	1194.0	.5	Sandstone; medium-brown, fine-grained to siltstone, micaceous, fossiliferous, argillaceous. Matrix material is clay (5 to 10 pct of rock volume). Quartz is light gray, angular (0.05 to 0.20 mm), and poorly sorted. Biotite and muscovite mica.
1194.0	1194.8	.8	Shale; light- to medium-gray, micaceous, with lenses of sandstone, medium-brown, fine-grained, micaceous, fossiliferous.
Lewis Run Sand			
1301.5	1302.7	1.2	Sandstone and shale. Sandstone is light brown to light gray, very fine-grained, very argillaceous. Shale is light greenish-gray, very silty, very sandy, micaceous, and fossiliferous. (Fossils are mostly pelecypods).
1302.7	1302.9	.2	Missing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Lewis Run Sand - Continued			
1302.9	1303.3	0.4	Shale; light brownish-gray, silty, fossiliferous, Streaks of light- to medium-brown, fine-grained, micaceous sandstone. Some streaks 1 inch thick.
1303.3	1303.6	.3	Missing.
1303.6	1304.3	.7	Sandstone; light-brown, fine-grained, slightly dolomitic. Matrix material is finely divided (clay size) mica and occupies 2 to 5 percent of rock volume. Sand grains are predominantly angular, white to glassy (0.17 to 0.25 mm), poorly sorted quartz grains. Traces of feldspar and pyrite. Streaks of gray shale and fossils.
1304.3	1304.6	.3	Missing.
1304.6	1305.4	.8	Shale; gray, silty, sandy, fossiliferous with sandstone stringers.
1305.4	1305.8	.4	Missing.
1305.8	1306.3	.5	Shale; brownish-gray, very silty and sandy, slightly micaceous, very hard. Streaks of light-brown sandstone.
1306.3	1306.6	.3	Missing.
1306.6	1307.3	.7	Shale; greenish-gray, silty, fossiliferous and sandstone. Medium-brown, fine-grained, slightly dolomitic.
1307.3	1307.7	.4	Missing.
1307.7	1308.5	.8	Sandstone; light-brown, fine grained (0.12 to 0.22 mm), slightly micaceous. Matrix material is mica clay and occupies 2 to 5 percent of rock volume. Sand grains are light gray to glassy, angular, poorly sorted quartz grains. Traces of feldspar, ankerite and dolomite. Streaks of gray shale.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Lewis Run Sand - Continued			
1308.5	1308.8	0.3	Missing.
1308.8	1309.2	.4	Sandstone; medium-brown, fine-grained (0.125 to 0.10 mm), slightly dolomitic, very argillaceous. Matrix material is clay and mica and occupies 10 to 20 percent of rock volume. Sand grains are angular, light gray to glassy, poorly sorted quartz grains. Somewhat shaly.
1309.2	1309.4	.2	Missing.
1309.4	1310.1	.7	Sandstone; light- to medium-brown, fine-grained (0.12 to 0.25 mm), argillaceous, slightly dolomitic. Matrix is clay and mica and occupies 5 to 20 percent of rock volume. Sand grains are light gray to glassy, angular, poorly sorted quartz grains. Stringers of clay material.
1310.1	1310.4	.3	Missing.
1310.4	1311.4	1.0	Sandstone; same as above.
1311.4	1311.6	.2	Missing.
1311.6	1312.3	.7	Sandstone; light-brown, fine-grained (0.10 to 0.19 mm), argillaceous, shaly. Matrix is clay and finely divided mica and occupies 5 to 10 percent of rock volume. Sand grains are light gray, angular, poorly sorted quartz grains. Shale is greenish-gray.
1312.3	1312.5	.2	Missing.
1312.5	1312.9	.4	Sandstone; light brownish-gray, fine grained (0.12 to 0.25 mm), very argillaceous, slightly dolomitic and calcareous. Matrix material is clay and occupies 15 to 25 percent of the rock volume. Sand grains are light gray, angular to subangular, poorly sorted, quartz grains. Traces of pyrite.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Lewis Run Sand - Continued			
1312.9	1313.4	0.5	Sandstone; light-brown, fine-grained (0.12 to 0.25 mm). Very argillaceous. Clay matrix occupies 15 to 30 percent of rock volume. Sand grains are light gray, angular to subangular, poorly sorted quartz grains.
1313.4	1313.8	.4	Missing.
1313.8	1314.2	.4	Sandstone; light-brown, fine-grained (0.12 to 0.25 mm), argillaceous, dolomitic. Matrix material is clay and occupies 5 to 20 percent of rock volume. Sand grains are clear to light gray, angular, and poorly sorted, quartz grains. Slightly fossiliferous (brachiopods).
1314.2	1314.5	.3	Missing.
1314.5	1315.2	.7	Sandstone; as above, except quite shaly and fossiliferous.
1315.2	1315.7	.5	Sandstone; light grayish-brown, fine-grained (0.12 to 0.25 mm), slightly dolomitic, shaly. Clay matrix composes 5 to 7 percent of rock volume. Sand grains are clear to light-gray, angular, poorly sorted quartz grains.
1315.7	1315.9	.2	Missing.
1315.9	1316.5	.6	Sandstone; light-brown, fine-grained (0.10 to 0.25 mm), slightly dolomitic, very shaly, micaceous. Matrix of clay occupies 5 to 7 percent of rock volume. Sand grains are clear to light-gray, subangular to angular, poorly sorted quartz grains. Shale is light gray, silty and sandy, and in streaks of 5 to 10 mm in thickness.
1316.5	1316.8	.3	Missing.
1316.8	1317.1	.3	Sandstone; as above, but slightly calcareous as well as dolomitic.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Lewis Run Sand - Continued			
1317.1	1317.5	0.4	Missing.
1317.5	1318.4	.9	Sandstone; light-brown, fine grained (0.125 to 0.250 mm), calcareous, dolomitic, very shaly, micaceous. Matrix material is clay and occupies 2 to 5 percent of rock volume. Porosity visible. Sand grains are angular to subangular, poorly sorted quartz grains. Shale is sandy, light green, and in streaks 5 to 10 mm in thickness, fossiliferous (brachiopods).
1318.4	1318.6	.2	Missing.
1318.6	1319.4	.8	Sandstone; as above, but shale streaks thicker (10 to 20 mm).
1319.4	1319.7	.3	Missing.
1319.7	1320.2	.5	Sandstone; light-brown, fine grained (0.10 to 0.25 mm), slightly calcareous, dolomitic, micaceous, very shaly, fossiliferous. Clay matrix occupies 5 to 7 percent of rock volume. Sand grains are clear to light gray, angular, poorly sorted quartz grains. Shale is light grayish-green. Streaks 5 to 10 mm in thickness.
1320.2	1320.5	.3	Missing.
1320.5	1321.7	1.2	Sandstone; light-brown, fine-grained (0.12 to 0.25 mm), slightly calcareous and dolomitic, micaceous, very shaly, fossiliferous. Clay matrix occupies 5 to 20 percent of rock volume. Sand grains are clear to light gray, angular, poorly sorted quartz grains. Shale is greenish-gray, sandy, micaceous and in streaks 10 to 20 mm thick.
1321.7	1322.0	.3	Missing.
1322.0	1322.3	.3	Sandstone; light-brown, shaly, as above.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Lewis Run Sand - Continued			
1322.3	1322.5	0.3	Missing.
1322.5	1323.0	.5	Sandstone; light-brown, fine-grained, (0.10 to 0.25 mm), slightly calcareous, micaceous, fossiliferous, very shaly. Clay matrix composes 10 to 15 percent of rock volume. Sand grains are clear to light gray, angular, poorly sorted quartz grains. Shale is light gray, sandy, and micaceous.
1323.0	1323.6	.6	Sandstone; light-brown, very fine- to fine-grained (0.075 to 0.240 mm), calcareous in zones, dolomitic, micaceous zones, fossiliferous, shaly. Matrix material is clay and carbonate and occupies 7 to 20 percent of rock volume. Sand grains are white to clear, subangular, poorly to fairly well sorted quartz grains. Shale is light gray, sandy, micaceous, and in streaks 3 to 5 mm in thickness.
1323.6	1323.9	.3	Missing.
1323.9	1324.1	.2	Sandstone; light-brown, fine-grained (0.12 to 0.25 mm), slightly calcareous and dolomitic, shaly. Clay matrix occupies 5 to 10 percent of rock volume. Quartz grains are angular, clear to light gray and poorly sorted. Shale is light gray in 10 mm streaks.
1324.1	1324.5	.4	Missing.
1324.5	1325.5	1.0	Sandstone; as above, except micaceous, and fossiliferous.
1325.5	1325.9	.4	Missing.
1325.9	1326.4	.5	Sandstone; light and dark-brown, fine-grained (0.09 to 0.22 mm), slightly calcareous, fossiliferous, shaly. Clay matrix material occupies 5 to 10 percent of rock volume. Quartz grains are clear to light gray, angular and poorly sorted. Shale stringers more frequent, approaching 50 percent of rock through interval observed.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Lewis Run Sand - Continued			
1326.4	1326.8	0.4	Sandstone as above.
1326.8	1328.4	1.6	Shale; light-gray, waxy, slightly sandy, fossiliferous, with thin (1 to 2 mm) sandstone stringers.
Sartwell Sand			
1584.9	1585.6	.7	Shale; light-gray, fossiliferous, slightly micaceous.
1585.6	1587.5	.9	Missing.
1587.5	1588.0	.5	Shale; light-gray, slightly sandy and micaceous, slightly calcareous. Small sandstone stringers 1 mm thick.
1588.0	1588.3	.3	Missing.
1588.3	1589.8	1.5	Shale; light-gray, slightly micaceous, laminated, with 1 mm thick sandstone stringers.
1589.8	1590.2	.4	Sandstone; dark-brown, fine-grained (0.09 to 0.25 mm), loosely bonded by mica clay. Quartz grains are clear to light gray, angular, poor to fairly well sorted and oil stained. Slightly micaceous.
1590.2	1590.6	.4	Shale; light-gray, slightly micaceous.
1590.6	1591.4	.8	Sandstone; light-brown, fine grained, (0.10 to 0.25 mm), micaceous, Quartz grains are angular, clear to light gray, poorly sorted, and loosely but rigidly bonded by clay (2 percent of rock volume), light oil stain.
1591.4	1591.8	.4	Shale; light-gray, slightly micaceous.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Sartwell Sand - Continued			
1591.8	1592.4	0.6	Sandstone; light-brown, fine-grained (0.10 to 0.25 mm), micaceous, slightly calcareous; matrix material of clay and mica occupies 5 to 10 per- cent of rock volume. Quartz grains are clear, angular, and poorly sorted.
1592.4	1593.0	.6	Shale; light-gray, slightly micaceous, fossiliferous.
1593.0	1593.6	.6	Sandstone; light-brown, fine-grained (0.09 to 0.25 mm), micaceous. Matrix material of clay and mica occupies 7 to 10 percent of rock volume. Quartz grains are clear, angular, and poorly sorted. One or two small shale partings.
1593.6	1594.4	.8	Sandstone; as above.
1594.4	1594.7	.3	Missing.
1594.7	1594.9	.2	Shale; light-gray, with sandstone streaks.
1594.9	1595.3	.4	Sandstone; light-brown, fine-grained (0.10 to 0.25 mm), slightly dolomitic, clay matrix material occupies 5 to 7 percent of rock volume. Quartz grains are clear, angular and poorly sorted, slight oil stain.
1595.3	1595.5	.2	Missing.
1595.5	1597.0	1.5	Shale; light-gray, fossiliferous, and sandstone; light-brown, interbedded.
1597.0	1597.6	.6	Sandstone; dark-brown, fine-grained (0.10 to 0.20 mm), micaceous, slightly shaly, slightly dolomitic. Quartz grains are clear, angular, poorly sorted, and loosely but firmly bonded by clay matrix material (2 to 7 percent of rock volume).
1597.6	1597.8	.2	Missing.

TABLE B-1. - Detailed lithologic description
of Crowley well 4 - Continued

Depth, feet		Thickness, feet	Rock Character
Top	Bottom		
Sartwell Sand - Continued			
1597.8	1598.6	0.8	Shale; light- to medium-gray, laminated, fossiliferous, and contains thin (1 mm) interbeds of light-brown sandstone.
1598.6	1598.8	.2	Missing.
1598.8	1599.3	.5	Sandstone; dark-brown, fine-grained (0.10 to 0.25 mm), dolomitic. Quartz grains are clear to glassy, angular, poorly sorted. Clay matrix occupies 5 to 7 percent of rock volume.
1599.3	1601.4	2.1	Shale; light-gray, laminated, micaceous, fossiliferous.

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